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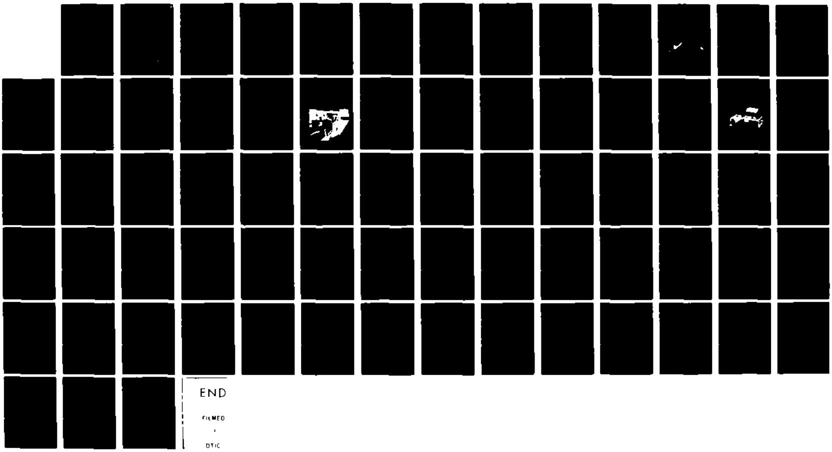

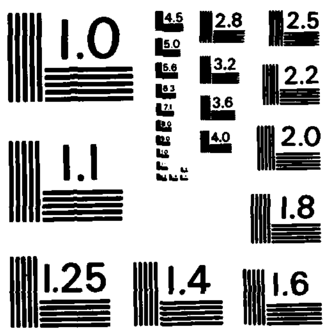
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Systems Research &
Development Service
Washington, D.C. 20591

LORAN-C Grid Calibration Requirements for Aircraft Non-Precision Approach

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July 1982

Final Report

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16. Abstract

The Federal Aviation Administration (FAA) Technical Center has conducted tests to measure spatial warpage and temporal instability in the Loran-C hyperbolic navigation grid. Airborne Loran-C calibration requirements identified from the test data are discussed in this report. The test results have been obtained in support of the Federal Radionavigation Plan decision process. Test emphasis is placed on non-precision approach, the flight phase for which FAA Advisory Circular AC-90-45A accuracy requirements are most stringent. Spatial warpage is assessed using Time Difference (TD) data collected at approximately 25 sites within 20 km of each of five airports. It is found that the Loran-C TD bias is the dominant warpage component and that the bias must be calibrated to meet AC-90-45A requirements for certain airports and station triads. An alternative but less accurate method than bias calibration makes use of propagation models based on mixed land/sea signal paths. Temporal instability is assessed using TD data collected over two-to-three week periods at each airport and over an entire year at a fixed-site monitor at London, KY. It is concluded that short-term instability is negligible, but seasonal instability is potentially a problem for certain regions and triads.

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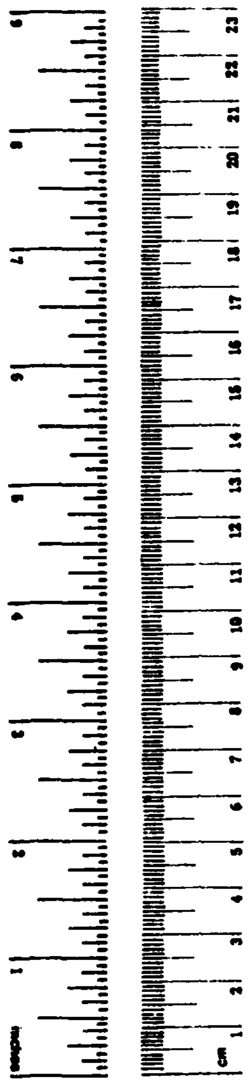
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

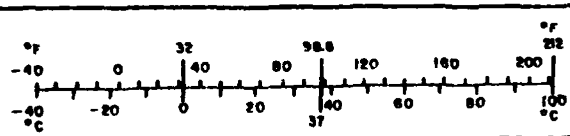
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The Loran-C tests described in this report were conducted by the FAA Technical Center (FAATC) for the FAA Systems Research and Development Service (SRDS). The Analytic Sciences Corporation (TASC), under contract to SRDS, was responsible for analyzing the test data and evaluating Loran-C system accuracy. The authors acknowledge the technical contributions made by the contract monitor, Mr. George Quinn of SRDS, and the test director, Mr. Robert Erikson of FAATC. The guidance of Mr. Ronald Warren, manager of the Navigation Systems Department at TASC, is also appreciated. Mr. Peter Clark of TASC developed a large portion of the Data Management System used to process the test data. Mr. Howard Meeks, Mr. Thomas Wisser, and Mr. William Yost of FAATC were the technicians responsible for test details.

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1. INTRODUCTION

1.1 BACKGROUND

The Federal Radionavigation Plan requires that the Departments of Transportation and Defense present recommendations in 1983, regarding the future implementation and operation of radionavigation systems (Ref. 1). In response to the Plan, the Federal Aviation Administration (FAA) is conducting an evaluation of candidate aircraft navigation systems, including Loran-C (see Fig. 1.1-1). Two questions which the evaluation seeks to answer are:

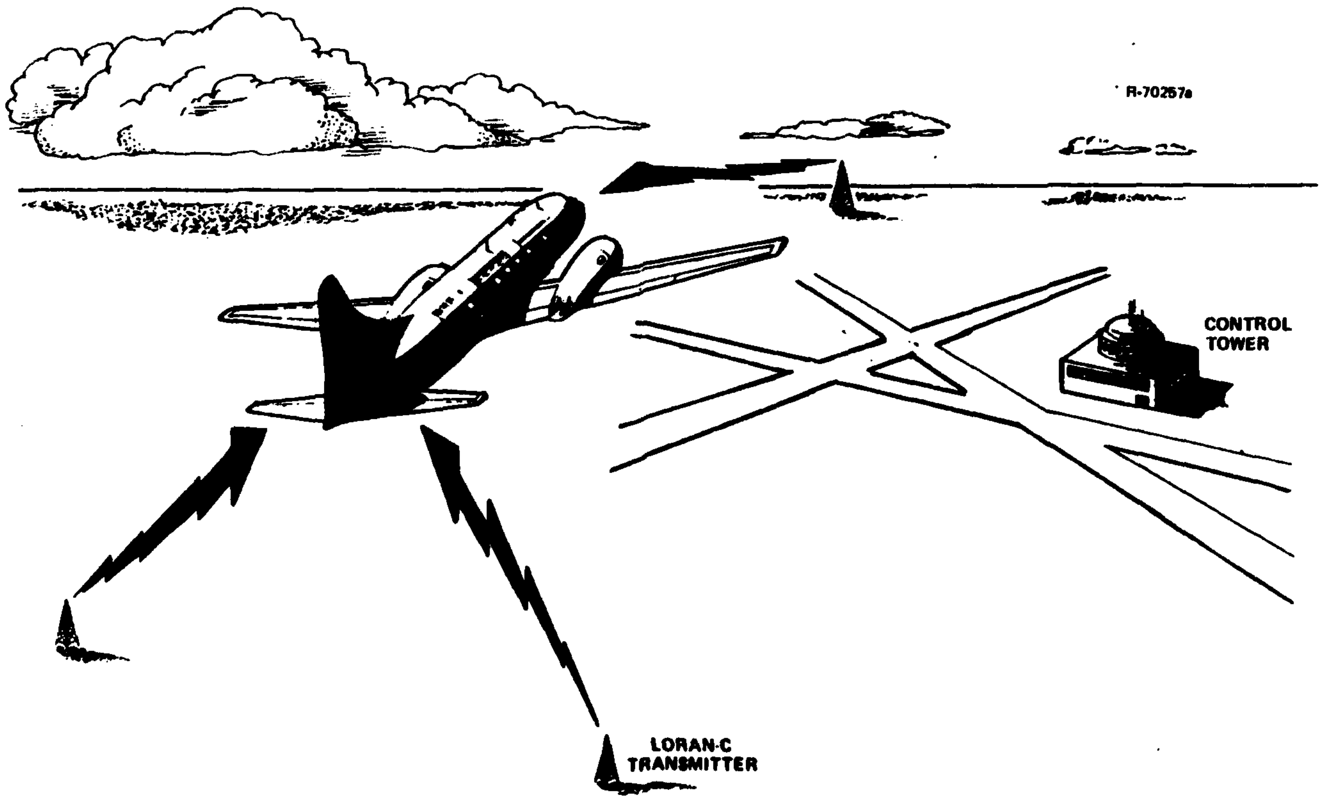


Figure 1.1-1 Loran-C: A Candidate Aircraft Navigation System

- What is the most cost-effective mix of aircraft navigation systems for the post-1995 era?

- Should Loran-C be certified for airborne use in the near term, particularly in regions not served by VOR/DME?

The FAA Loran-C evaluation program includes ground-based tests, flight tests, equipment development activities, coverage/ reliability analyses, and cost analyses. Ground-based Loran-C accuracy tests were conducted by the FAA Technical Center (FAATC) for the FAA Systems Research and Development Service, from May 1981 to April 1982. The results of the FAATC tests are presented in this report.

Airborne equipment error requirements for operation in the U.S. National Airspace System are given in FAA Advisory Circular AC-90-45A (Ref. 2). The requirements for enroute, terminal, and non-precision approach flight phases are presented in Table 1.1-1. For the general case of nonzero-mean cross-track and along-track errors, the AC-90-45A requirements are limits on the "mean + 2σ" error. Enroute and terminal accuracy requirements are typically satisfied by Loran-C without grid calibration, a fact acknowledged by the FAA issuance of a Supplemental Type Certificate for enroute/terminal use of the Texas Instruments TI-9100 receiver (Ref. 3).

TABLE 1.1-1

AC-90-45A AIRBORNE EQUIPMENT
ERROR REQUIREMENTS

FLIGHT PHASE	CROSS-TRACK OR ALONG-TRACK ERROR (MEAN + 2σ)
Enroute	1.5 nm, 2800 m
Terminal	1.1 nm, 2000 m
Non-Precision Approach	0.3 nm, 550 m

Flight tests have shown that non-precision approach accuracy requirements are satisfied by uncalibrated Loran-C for the preferred (primary) station triad (MWX) in Vermont (Ref. 4). However, the same tests have shown that the second-best triad (MWY) exhibits a 2-nm north position error, which must be calibrated to meet AC-90-45A requirements. Other flight tests have indicated that non-precision approach requirements are not satisfied without calibration -- e.g., at South Lake Tahoe, California for either the primary or second-best triad (Ref. 5). The FAATC Loran-C tests focus on calibration requirements for non-precision approach and the trade-off between calibration and improved receiver-based propagation models.

1.2 TEST OBJECTIVES

The major Loran-C error source is uncertainty in the propagation velocity of the groundwave signal, especially for land paths. This uncertainty leads to errors in the Line of Position (LOP) associated with each Time Difference (TD) measurement and, consequently, to position-fix errors. Distortion in the ideal hyperbolic LOP at any particular time is termed grid warpage, while changes in the LOP with time are termed grid instability (see Fig. 1.2-1). Grid warpage, which governs Loran-C geodetic accuracy, can be reduced by improved receiver-based propagation models or by grid calibration. Ideally, a single model or calibration will apply over the entire year. In reality, the model/calibration parameters may have to be updated periodically due to grid instability, which limits Loran-C repeatability.

The objective of the FAATC tests reported herein was to collect Loran-C data conducive to the isolation and assessment of grid warpage and instability. To meet this objective, it was necessary to revisit test sites and to dwell at sites

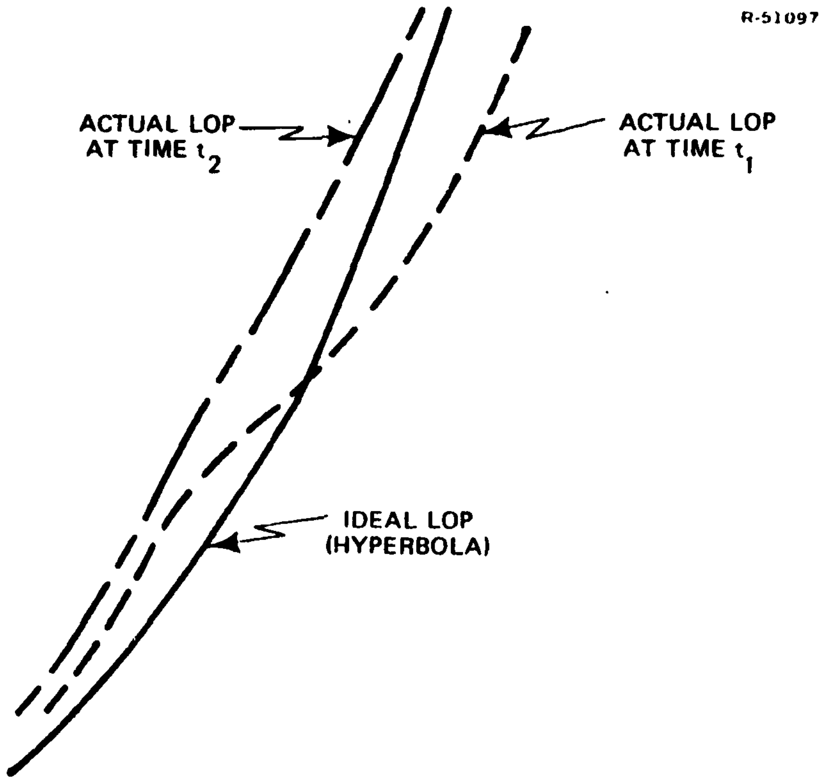


Figure 1.2-1 Warpage and Instability in the Loran-C Hyperbolic LOP

for extended time periods, both dictating a ground-based test program. Airborne Equipment Errors during flight are expected to be somewhat different than those measured on the ground, due to the wider receiver noise bandwidth (reduced averaging time) required on a moving aircraft and the change in grid warpage with altitude. It is recommended that the difference, which is estimated to be small, be measured with a modest flight test program. Measurement of Flight Technical Errors, an AC-90-45A error category separate from Airborne Equipment Errors, requires more extensive flight testing.

Grid warpage and instability data were obtained by the mobile FAATC Test Van and stationary Loran-C monitors, respectively. Although similar ground tests have been conducted in the past by other organizations, the FAATC tests are unique in their specialization to non-precision approach. An indepth

review of past tests was conducted to minimize duplication and guide the interpretation of the FAATC test data (Ref. 6). The literature review is summarized in Appendix A.

1.3 REPORT OVERVIEW

The Loran-C test program documented herein represents a closely coordinated effort between FAATC and The Analytic Sciences Corporation (TASC): FAATC personnel directed and conducted the tests, preprocessed the test data, and furnished the data tapes to TASC in a prescribed format; TASC personnel edited the data tapes, constructed an easily-accessed Loran-C data base, and conducted all data analyses.

Chapter 2 presents a description of the FAATC tests. The instrumentation employed in the FAATC Test Van and at the stationary monitors is described, and the rationale behind the selection of test sites is reviewed. Additional details regarding instrumentation and site selection are contained in the test plan (Ref. 7). Also discussed in Chapter 2 is the independent method used to obtain site geodetic coordinates for comparison to the Loran-C data.

Test results are presented in Chapter 3. The data analysis methodology is outlined, including the candidate propagation models, selected Loran-C performance index, and data-editing procedure. The impact of grid warpage on non-precision approach accuracy is assessed for the two Loran-C error correction philosophies: receiver-implementation of improved propagation models and user-entry of calibration corrections. Model/calibration updating requirements driven by grid instability are then discussed. The systematic analysis of the FAATC test data leads to definitive conclusions regarding the tradeoffs between models and calibration.

The conclusions and recommendations presented in Chapter 4 are key inputs to the Federal Radionavigation Plan decision process. Recommendations are made based on Loran-C accuracy alone. These must be interpreted in the context of the overall FAA Loran-C evaluation, which also includes coverage, reliability, and cost analyses. Included in the recommendations are requirements for expanded Loran-C accuracy tests to answer questions not addressed in the current FAATC tests.

2. TEST DESCRIPTION

2.1 OVERVIEW

The FAATC tests provide a sufficient data base to answer fundamental Loran-C grid warpage and instability questions, consistent with current FAA program objectives. Three test facilities are employed:

- Test Van
- Airport Monitor
- Fixed-Site Monitor.

The characteristics of each facility are given in Table 2.1-1. Grid warpage is measured by the mobile FAATC Test Van, which is used to visit approximately 25 sites near each of five airports. Data are recorded at each site for 30 min. Because the data from different sites are not synchronous in time, a stationary Airport Monitor is established. The Airport Monitor records grid instability data during the period of Test Van operations (approximately two weeks per airport), for use in post-mission synchronization of the Test Van data. The Test Van visits each airport twice during the test year, once in the summer and once in the winter. However, the principal source of seasonal grid instability data is a Fixed-Site Monitor at London, KY, which operates continuously over the entire test year.

Instrumentation, procedures, and site selection for the three test facilities are described in Sections 2.2 to 2.4. The method used to obtain site geodetic coordinates from

TABLE 2.1-1

NOMINAL TEST FACILITY CHARACTERISTICS

CHARACTERISTIC	TEST FACILITY		
	TEST VAN	AIRPORT MONITOR	FIXED-SITE MONITOR
Principal Data Type	Warpage	Instability	Instability
Receiver	Austron 5000	Micrologic ML-220	Micrologic ML-220
Sites	5 Airports, 25 Sites Each	5 Airports, 1 Site Each	London, KY*
Time Per Site	30 min (Once or Twice per yr)	2 wk	1 yr
Sampling Interval	1 min	1 min†	15 min

*Second planned monitor at Buffalo, NY failed due to instrumentation malfunctions.

†Interval is 10 sec for selected periods of 2-3 hr.

U.S. Geological Survey (USGS) topographic maps is discussed in Section 2.5. Additional test details are contained in the test plan (Ref. 7).

2.2 TEST VAN

2.2.1 Instrumentation

The FAATC Test Van is a GMC Magna Van, modified to house the test instrumentation and reduce local interference such as ignition noise. The self-contained 110/220 VAC generator is located in a steel enclosure, isolated from the Test Van interior by marine-class Radio Frequency Interference (RFI) shielding. Power enters the Test Van interior through screen-room line filters, which reduce conducted interference. An

uninterruptable power supply provides battery power for 10 min in the event of generator failure.

The Test Van constitutes a self-contained laboratory, capable of signal reception, data recording, and preliminary data processing. The Test Van instrumentation, shown in Fig. 2.2-1, can be divided into three groups:

- Loran-C Receiver System
- Spectrum Analyzer System
- Calculator System.

The systems are shown in simplified block diagram form in Fig. 2.2-2 and are discussed in subsequent paragraphs.

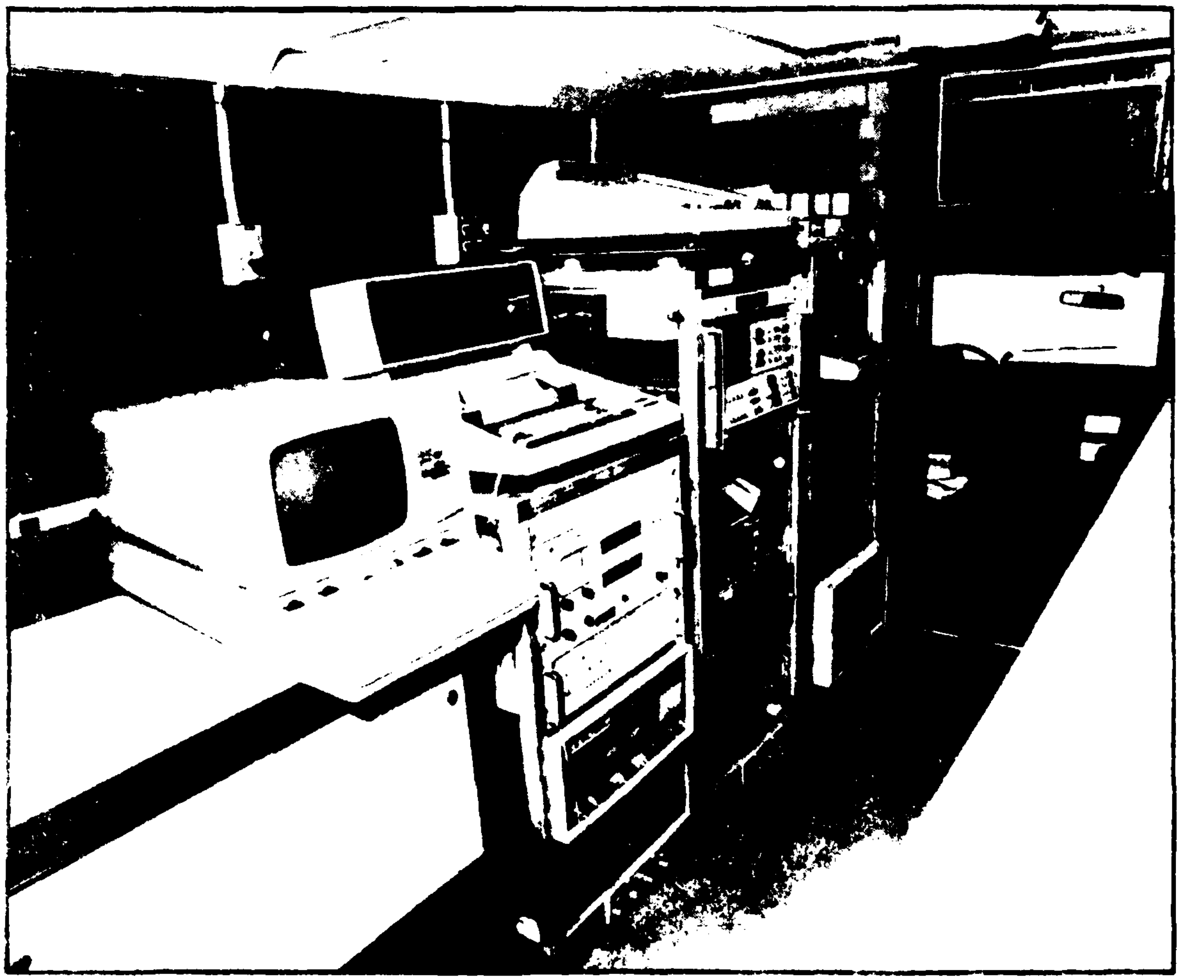


Figure 2.2-1 Test Van Instrumentation

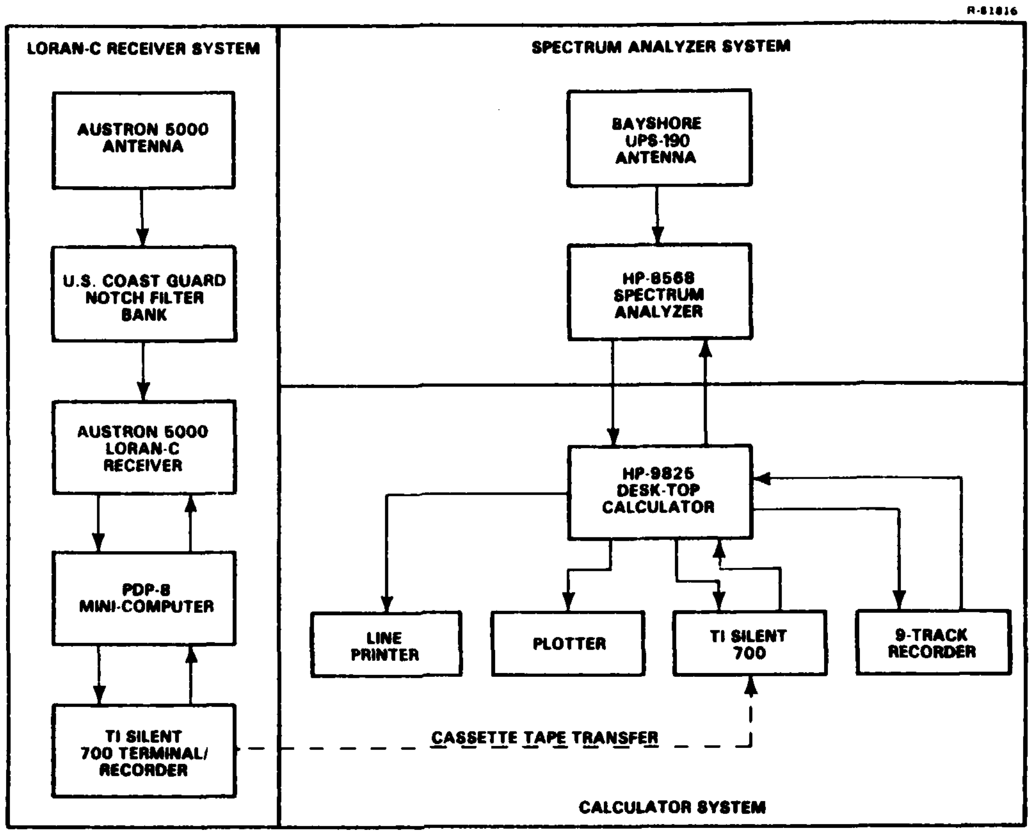


Figure 2.2-2 Three Test Van Systems

The Loran-C receiver system centers around the Austron 5000 precision receiver used by the U.S. Coast Guard to monitor and control the chains. The whip antenna is mounted vertically on the Test Van roof and removed during transit. Signals enter through a passive coupler and a notch filter bank supplied by the U.S. Coast Guard. The notch filter bank includes 12 filters, pre-tuned to signals known to interfere with Loran-C reception in the Northeast U.S. chain. The Austron 5000 receiver operates in conjunction with a PDP-8 mini-computer, which interfaces with a Texas Instruments Silent 700 terminal/ recorder. The Silent 700 includes a digital cassette system for loading the PDP-8 software and recording the Loran-C data. The following parameters are recorded once per minute for all Northeast U.S. chain signals: TD, Signal-to-Noise Ratio (SNR), Envelope-to-Cycle Difference (ECD), receiver mode, and receiver

gain. Time of Arrival (TOA) data are also recorded, but with respect to the internal crystal oscillator rather than a cesium standard.

The spectrum analyzer system serves to detect potential RFI problems at the Test Van sites. The system is comprised of a Hewlett Packard HP-8568 spectrum analyzer coupled to a Bayshore UPS-190 active antenna. Because the Bayshore antenna is short enough to remain mounted on the Test Van roof during transit, it is possible to examine the spectrum while searching for a suitable site. Standard spectra are plotted at each selected site to completely document the RFI/noise environment.

The calculator system consists of a Hewlett Packard HP-9825 desk-top calculator, with the following peripherals:

- Line Printer
- Plotter
- Nine-Track Tape Recorder
- TI Silent 700 Terminal.

This system enables the test engineer to evaluate the Loran-C data quality on site, and to record all relevant information for future analysis. Among the outputs of the calculator system are: Loran-C data plots, statistical summaries, and hard copies of the spectrum analyzer display.

2.2.2 Site Selection

The FAATC Test Van is used to measure grid warpage at five airports in the Northeast U.S. chain coverage area (see Fig 2.2-3). Airport selection is based on geographic features and scheduling logistics. Local geography is of greater interest in the selection process than is the entire

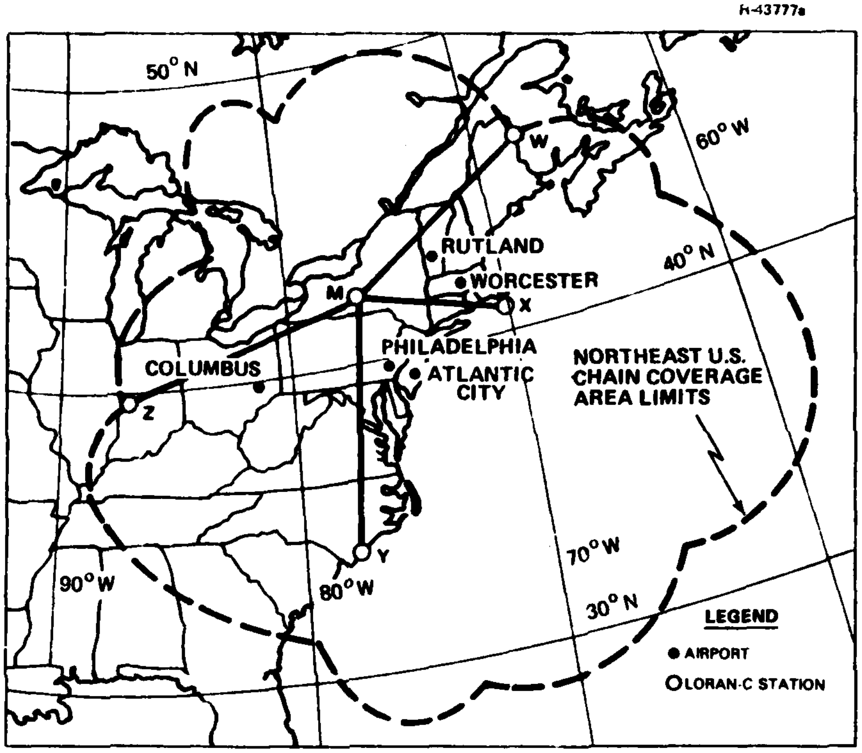


Figure 2.2-3 Airports Selected for Grid Warpage Tests

station-to-airport geography. The latter determines the grid bias which is convenient to calibrate, while the former determines the "random" grid warpage which limits calibration effectiveness. The selected airports represent distinct local geographic features:

- Atlantic City, NJ -- sea/land interface
- Philadelphia, PA -- intense development
- Columbus, OH -- flat terrain
- Worcester, MA -- hilly terrain
- Rutland, VT -- mountainous terrain.

The distances from Atlantic City to Philadelphia and from Worcester to Rutland are 80 km and 180 km, respectively. Data from these airport pairs are used to assess the spatial variability of the grid bias.

Approximately 25 sites are selected in the "approach area" of each airport, permitting the measurement of both the bias and random grid warpage components. For test purposes, the approach area is defined as a circle with a 20-km radius, centered on the Airport Reference Point (ARP). This definition covers the Outer Markers for most U.S. airports. Test Van sites are selected along runway extensions and LOP gradients where possible. The interest in LOP gradients stems from the desire to obtain a measurement of <u>worst-case</u> grid warpage for the airport (Ref. 7). An attempt is made to space the sites 5 km apart along each runway extension or LOP gradient. Some compromise is necessary, however, particularly where lakes, marshes, mountains, and the ocean prevent access by the Test Van. A typical distribution of sites is shown in Fig. 2.2-4 for the Atlantic City airport.

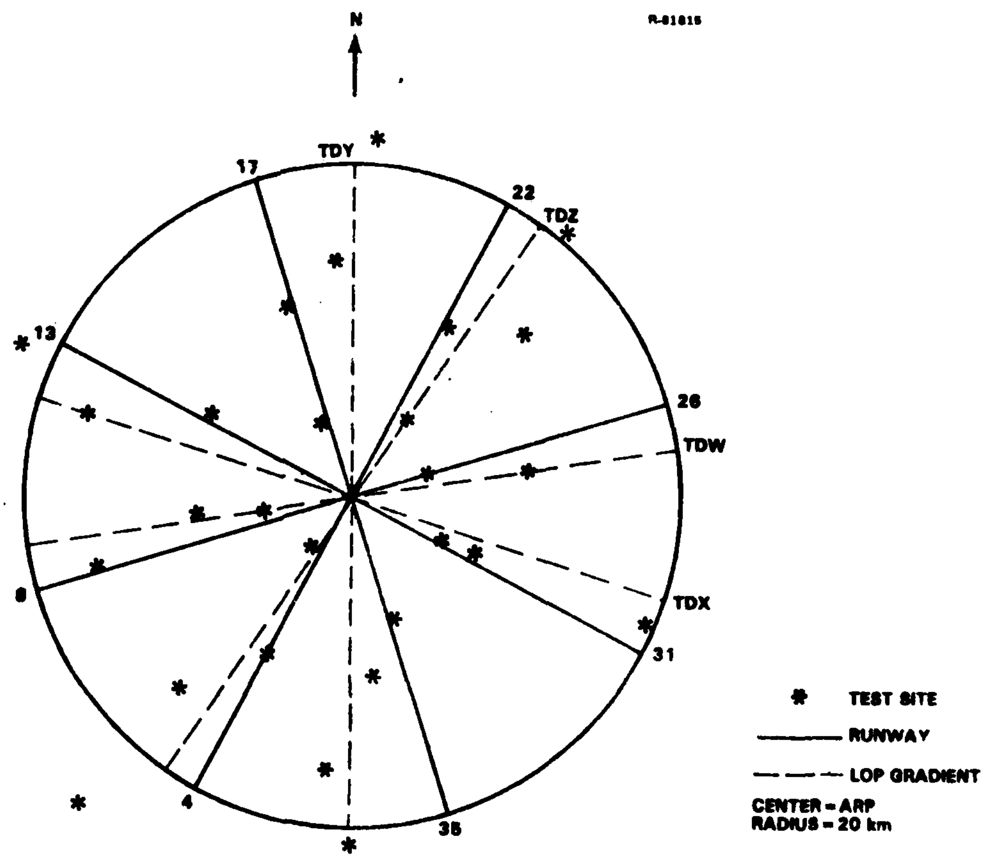


Figure 2.2-4 Atlantic City Airport Test Van Sites

Final site selection is conducted in the field to assure:

- Accessibility by the Test Van
- Proximity to benchmarks/landmarks shown on USGS topographic maps
- Removal from traffic, trees, power lines, and industry
- Freedom from high noise levels and RFI.

The test philosophy is to avoid reception problems not likely to be encountered in the airborne environment.

2.2.3 Procedures

Three sites are typically visited by the Test Van each day. The following procedure is carried out for each site:

1. Confirm the existence of the nearest benchmark
2. Examine the frequency spectrum
3. Select a specific site location
4. Read the site geodetic coordinates from a USGS map
5. Predict TDs for the site using the geodetic coordinates in a simple propagation model
6. Initiate Austron 5000 operations, using the predicted TDs to aid cycle identification if necessary
7. Record Loran-C data for 30 min at a 1-min sampling rate
8. Plot the frequency spectra

9. Mark the site by a spike or paint

10. Sketch the site in relation to landmarks.

Graphs and statistics of the TD, SNR, and ECD data for all sites are generated at day's end, to confirm the recording and consistency of the data. If the measured TDs are inconsistent with the grid bias observed at previous sites, the tests are repeated on a subsequent day.

Approximately two weeks are required to complete the measurements at all sites at an airport. Each airport is visited once in the "summer" (May-October, 1981) and once in the "winter" (February-March, 1982). Based on the summer test results, it was determined that winter test objectives can be met with fewer sites (see Table 2.2-1). Winter tests at Philadelphia and Rutland are limited to five sites each, one at the airport and the others on the approach area perimeter.

TABLE 2.2-1
NUMBER OF TEST VAN SITES

AIRPORT	NUMBER OF SITES	
	SUMMER	WINTER
Atlantic City	28	17
Philadelphia	20	5
Columbus	29	17
Worcester	31	18
Rutland	20	5

2.3 AIRPORT MONITOR

An Airport Monitor is established in a suitable building on the airport grounds, prior to commencing Test Van operations. The Airport Monitor instrumentation consists of a

Micrologic ML-220 Loran-C receiver and antenna, an MFE 2500 digital tape recorder, and an uninterruptable power supply (see Fig. 2.3-1). FAATC personnel reverse or change the cassette tape each morning and leave the instrumentation unattended for the duration of the test day. The following parameters are recorded once per minute for the Northeast U.S. chain signals: TD, SNR, ECD, receiver mode, and blink indicator. On selected occasions, a 10-sec sampling interval is employed for a period of 2-3 hr to assess the noise content of the data.

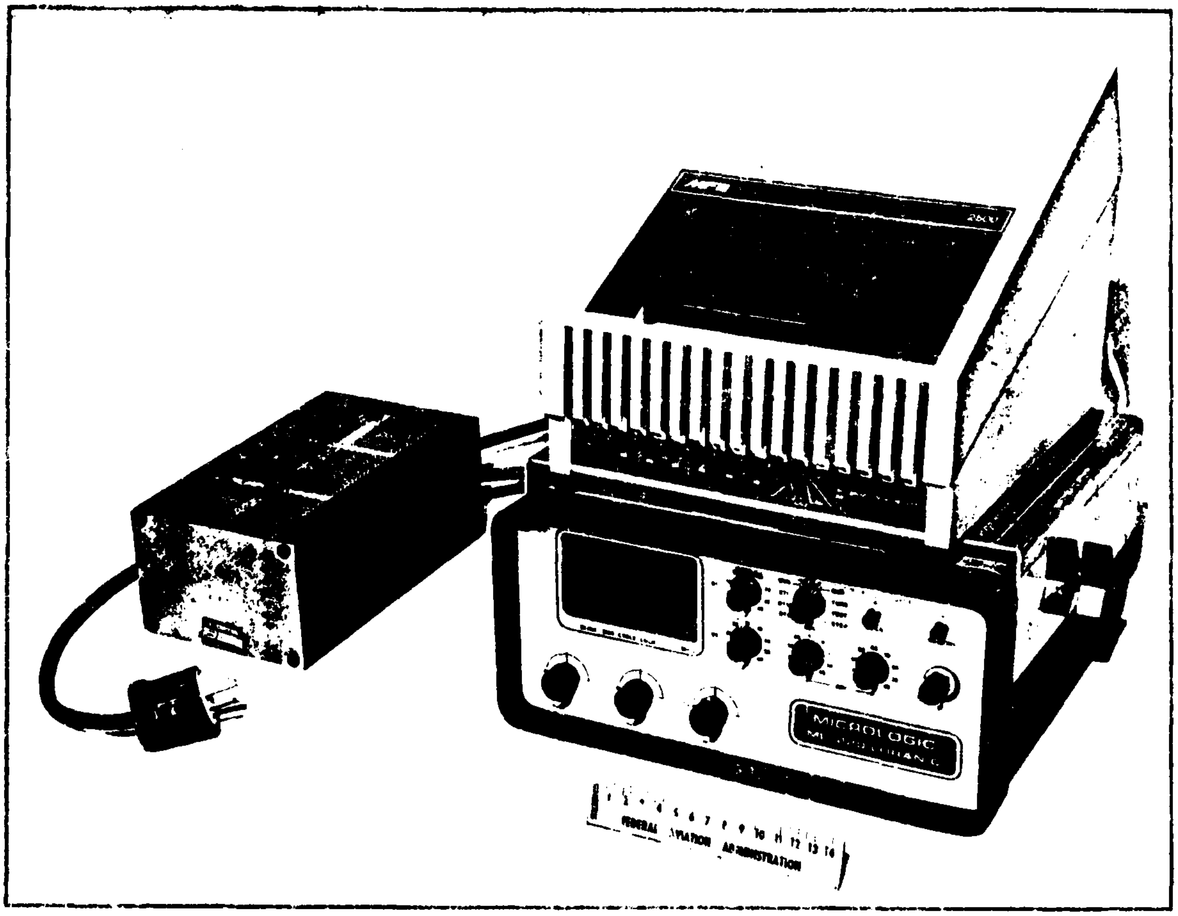


Figure 2.3-1 Airport Monitor Instrumentation

To reconcile possible TD offsets between the Austron 5000 and Micrologic ML-220 receivers, one Test Van site is selected in the vicinity of the Airport Monitor antenna. Austron 5000

data are recorded at this site for a 30-min period, just as for other Test Van sites. However, data are also recorded at this site at the beginning and end of each test day, to check the consistency of the offsets.

2.4 FIXED-SITE MONITOR

Although the Test Van provides data on the TD shifts between summer and winter, it is important to have a continuous TD record over the entire year. This requirement is satisfied by a Fixed-Site Monitor at the London, KY Flight Service Station. Fixed-Site Monitor instrumentation is identical to the Airport Monitor instrumentation described in Section 2.3. Northeast U.S. chain data are recorded every 15 min between May 1981 and April 1982. Flight Service Station personnel are required to check the receiver daily, reverse or change the cassette tape weekly, and mail the completed tapes to FAATC.

Grid instability is not uniform throughout the Loran-C chain coverage area. Instability is controlled to ±0.1 μsec at the System Area Monitor (SAM) and, to first order, increases in proportion to the "hyperbolic distance" from the SAM (Ref. 7). Hyperbolic distance contours for TDY, which is controlled by the SAM at Sandy Hook, NJ, are shown in Fig. 2.4-1. Because the hyperbolic distances from the TDY and TDZ SAMs are both quite large (400 nm and 250 nm, respectively), it is expected that grid instability impacts the primary triad (MYZ) in the London region to a greater extent than the primary triad in most other regions. To validate this hypothesis, it will be necessary to establish a network of Fixed-Site Monitors throughout the chain coverage area in future tests. A second Fixed-Site Monitor was initially established at the Buffalo, NY Flight Service Station, but was removed due to recorder malfunctions.

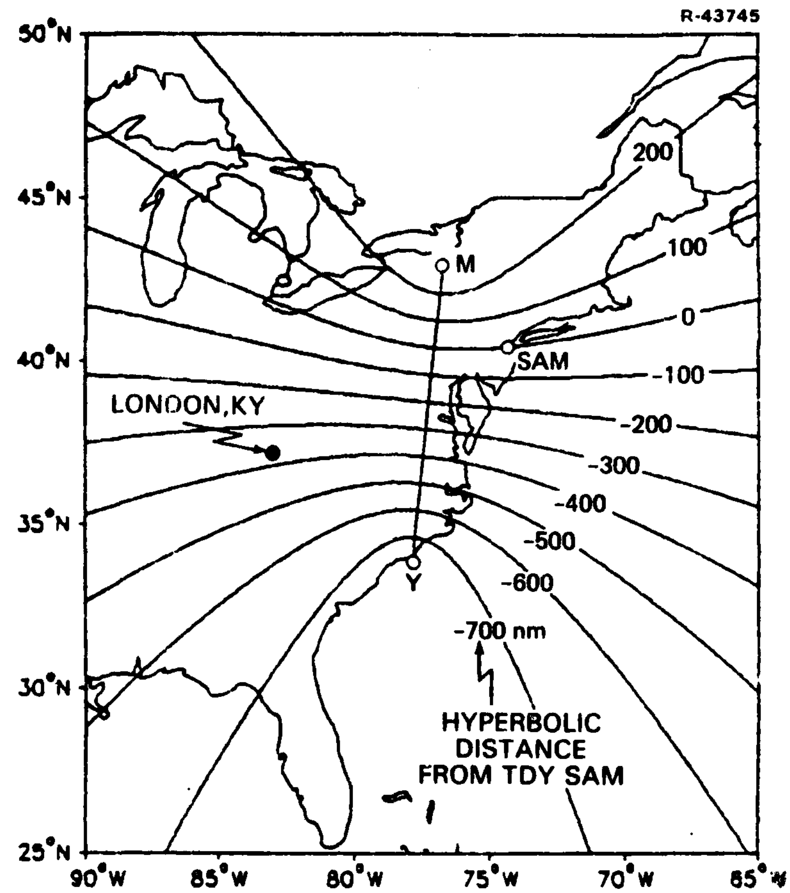


Figure 2.4-1 London, KY Fixed-Site Monitor Relative to TDY SAM

2.5 SITE GEODETIC COORDINATES

An independent measurement of the geodetic coordinates of the test sites is required to evaluate Loran-C accuracy. The desired geodetic coordinates are latitude and longitude referenced to the World Geodetic System (WGS-72) datum. The coordinates are obtained by FAATC personnel using the following map-based technique:

1. Measure the distance from the site to landmarks shown on a USGS topographic map

2. Pinpoint the site on the map

3. Read the North American Datum (NAD-27) coordinates for the site from the map

4. Convert these coordinates to WGS-72 coordinates, using the Abridged Molodensky formulas (Ref. 25).

An error budget for the technique, based on an error analysis conducted by FAATC personnel (Ref. 8), is presented in Table 2.5-1. Two error components are dominant: map-reading errors and datum offsets.

TABLE 2.5-1

USGS MAP GEODETIC COORDINATE ACCURACY

ERROR COMPONENT	VALIDATION BASIS	RMS POSITION ERROR (m)
Map Construction	Well-Defined Features Are Plotted On Map To 0.25-mm Accuracy (90%)	4
Site Measurements	Distances From Site To Features Are Measured With Tape	1
Map Readings	Coordinates Are Read By Three People Until Spread Is Less Than 60 m	15
Datum Offsets	Offsets Have Been Measured By the National Geodetic Survey Using Transit	14
Total	Surveyor Data From 27 New Jersey Sites	21

Map-reading errors are minimized by requiring that three people read the coordinates until they agree to within 60 m (interpreted as $\pm 2\sigma$). Datum offsets, associated with the

original reconciliation of local/state coordinate systems with the NAD-27 datum, have been measured with Transit by the National Geodetic Survey (Ref. 26). The datum offsets for the five airports at issue here range from 11 m to 16 m (14 m rms). The total rms position error for the map-based technique is 21 m, which is confirmed by surveyor (triangulation) data for 27 of the New Jersey sites. This error is negligible relative to AC-90-45A requirements and is less than 10 percent of the measured Loran-C rms errors.* It is concluded that site geodetic coordinates obtained from USGS maps are sufficiently accurate to meet all FAATC test objectives.

*The "measured Loran-C rms error" is taken to be the root-sum-square of "true Loran-C rms error" and "map rms error".

3. TEST RESULTS

3.1 OVERVIEW

The FAATC Loran-C test data are analyzed to assess the impact of grid warpage and instability on non-precision approach navigation accuracy. The assessment is conducted for the generic coordinate conversion software configuration shown in Fig. 3.1-1. In this configuration, TDA and TDB are the Time Difference readings from the receiver used in the tests (Austron 5000 or Micrologic ML-220). As many as three corrections are applied to each TD before computing the hyperbolic position fix:

- Emission delay -- published by the U.S. Coast Guard

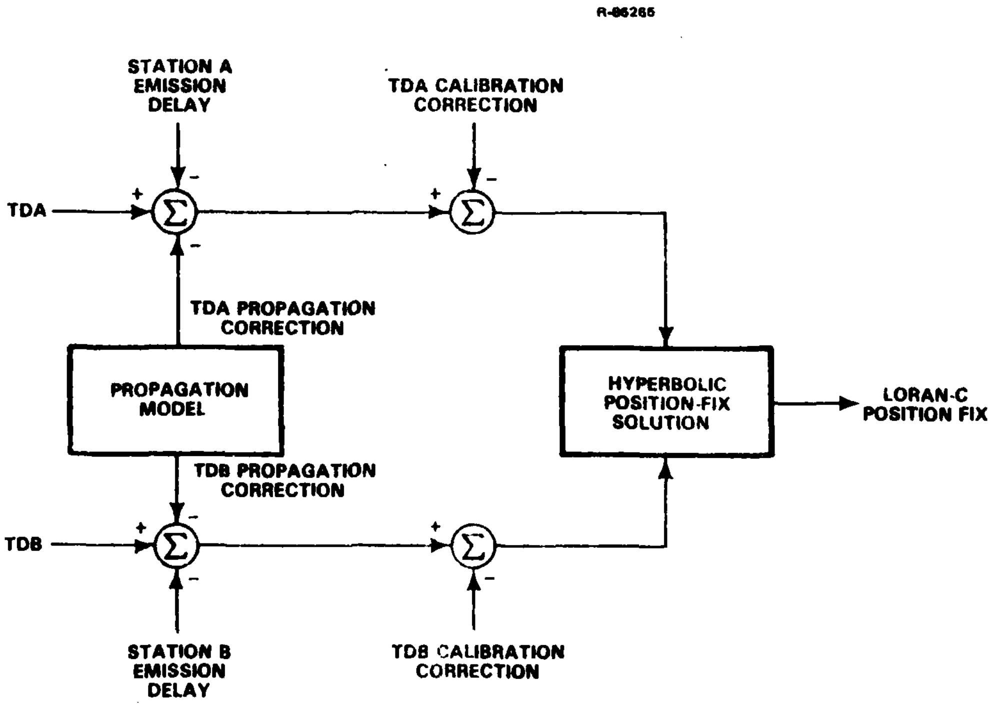


Figure 3.1-1 Coordinate Conversion Software Configuration

- Propagation correction -- based on a candidate signal propagation model

- Calibration correction -- based on TD data from one or more sites.

The Loran-C error is given by the difference between the Loran-C position fix and the known site geodetic coordinates.

If the receiver manufacturer implements an accurate propagation model, there may be no need for user-entered calibration corrections. However, the user may be willing to enter calibration corrections in return for a lower-cost receiver. The importance of the model/calibration tradeoff issue is reflected in the selected data analysis strategy. First, the performance of various models is evaluated using the grid warpage data; then, calibration is considered as an alternative to the models; and finally, the grid instability data are analyzed to determine model/calibration updating requirements.

Three aspects of the analysis methodology are described in Section 3.2: the candidate propagation models, selected performance index, and data-editing procedure. Grid warpage and instability test results are presented in Sections 3.3 and 3.4, respectively. Section 3.5 is a discussion of the test results in the context of Loran-C certification.

3.2 METHODOLOGY

3.2.1 Propagation Models

The five propagation models evaluated in this report are summarized in Table 3.2-1. The models are representative of the different levels of sophistication encountered in Loran-C receivers today, but do not necessarily duplicate the software of particular manufacturers. Model details are given in Ref. 7.

TABLE 3.2-1

CANDIDATE PROPAGATION MODELS

MODEL	ASSUMED PATH PROPERTIES	COMPLEXITY
Baseline	Standard Atmosphere; Earth's Presence Ignored	Low
Sea	All Sea Water (Conductivity = 5 mho/m)	Low
Land	All Average Land (Conductivity = 0.003 mho/m)	Low
Mixed	Segments of All Sea Water and All Average Land; Millington's Method Used	Medium
DMA	Segments Defined by Five-Level DMA Conductivity Map; Millington's Method Used	High

The baseline model assumes that the signal paths consist of a standard atmosphere, the Earth's presence being ignored. The term "baseline" is used because the propagation corrections indicated in Fig. 3.1-1 are zero for the baseline model. Propagation corrections for the other models are referenced to the baseline model. The sea model assumes that the paths are all sea water with a conductivity of 5 mho/m, while the land model assumes that they are all average land with a conductivity of 0.003 mho/m. The sea and land models are represented by fifth-order polynomials in transmitter/receiver range.

The mixed model is based on a path approximation consisting of segments of all sea water and all average land. Millington's method is used to compute the propagation corrections for the mixed path (Ref. 9). Implementation of the mixed model would require storage of the digitized coastline in receiver memory.

The most sophisticated propagation model evaluated herein employs the five-level conductivity map maintained by the Defense Mapping Agency (DMA) Hydrographic/Topographic Center. The DMA model is based on this conductivity map and Millington's method. The required propagation corrections were computed by DMA personnel and supplied to TASC. Receiver implementation of a digitized conductivity map is practical with current microcomputer technology, as evidenced by the ONI-7000 Loran-C receiver manufactured by Advanced Navigation, Inc.

3.2.2 Performance Index

FAA Advisory Circular AC-90-45A requires that the "mean + 2σ" cross-track and along-track errors for non-precision approach be less than 550 m (Ref. 2). The "mean + 2σ" error for a nonzero-mean Gaussian error distribution is indicated in Fig. 3.2-1. The fraction of samples within the "mean + 2σ" bounds ranges from 95% to 97.5%, depending on the relative values of the mean and standard deviation. The ensemble of error samples implied by the distribution must be collected

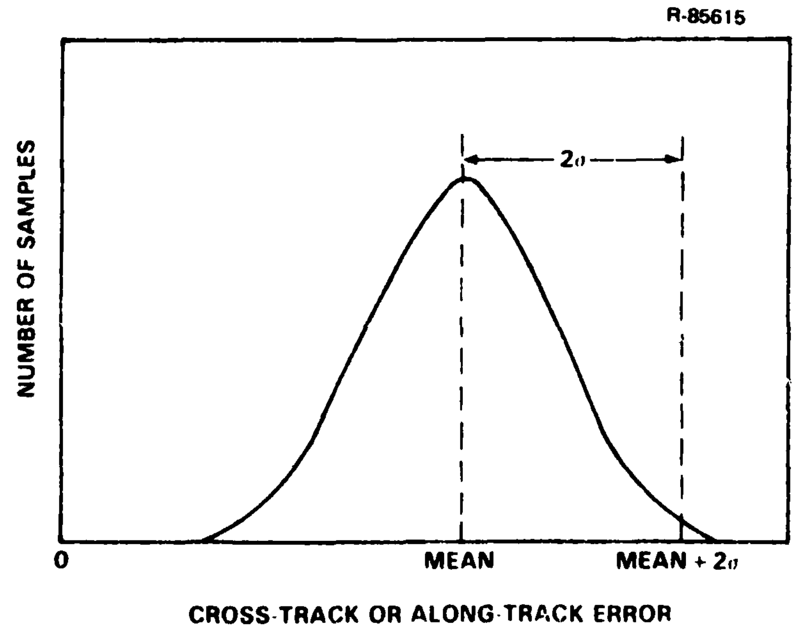


Figure 3.2-1 "Mean + 2σ" Error Definition

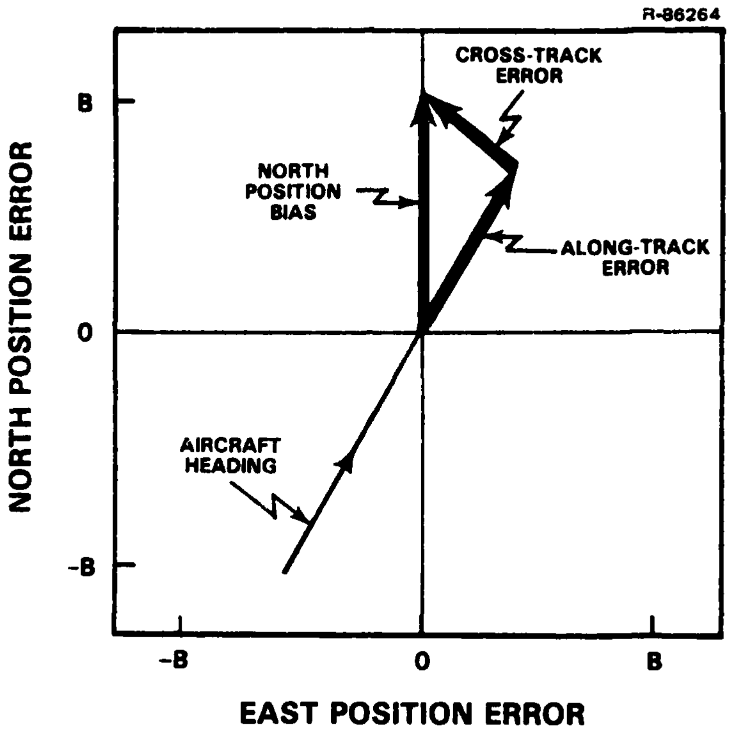
on the approach to a single runway. In the FAATC tests described in this report, it was feasible to select three or four Test Van sites on each runway extension (e.g., see Fig. 2.2-4). The number of sites is too small to reliably compute the "mean + 2σ" error for each runway, but the total number of sites for all runways and LOP gradients (nominally, 25) is sufficient to compute a Loran-C performance index for the airport.

Performance index selection is based on the following observation: the dominant grid warpage component in an airport approach area is a bias offset in the LOP for each TD. LOP biases result in north and east position biases, which resolve into cross-track and along-track errors for the aircraft heading of interest (e.g., see Fig. 3.2-2a). The cross-track and along-track errors are sinusoidal functions of heading, with equal amplitudes but a 90-deg phase offset (e.g., see Fig. 3.2-2b). Because the sinusoidal relationships are followed closely by the test data, these ideal relationships are assumed in the discussion below.

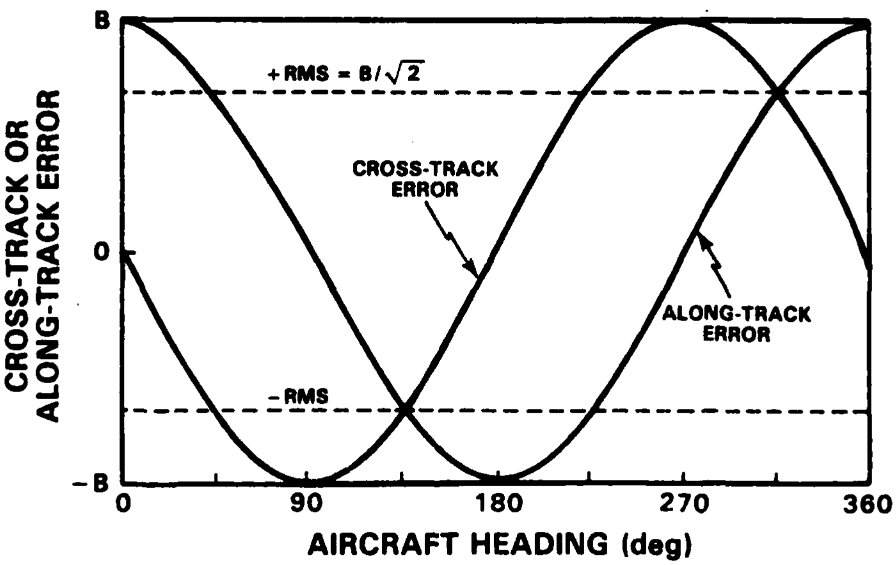
The selected performance index is the "rms cross-track error" computed over all headings. In the example shown in Fig. 3.2-2b, the rms cross-track error equals $B/\sqrt{2}$, where B is the magnitude of the bias. (Note that the "rms along-track error" is an equivalent index.) From Fig. 3.2-2b, it is seen that either the cross-track error or the along-track error exceeds (or equals) the rms cross-track error at every heading. The implications of this property are:

- If rms cross-track error > 550 m, all headings are unacceptable
- If rms cross-track error ≤ 550 m, some headings are acceptable.

Therefore, the rms cross-track error indicates whether or not headings exist for which Loran-C satisfies AC-90-45A requirements.



a) Bias Resolution



b) Heading Dependency

Figure 3.2-2 Cross-Track and Along-Track Errors for Pure North Position Bias

An alternative performance index, the "maximum cross-track error" over all headings (B in Fig. 3.2-2b), was considered but rejected. This performance index indicates whether or not <u>all</u> headings satisfy AC-90-45A requirements. Besides being more restrictive, the maximum cross-track error is unduly influenced by "abnormal" sites which are not representative of the ensemble of sites. The rms cross-track error instead characterizes the "typical" site and runway.

3.2.3 Editing Procedure

The FAATC test data are processed at TASC using an automated Loran-C Data Management System, which conducts sorting, editing, and reformatting operations (Ref. 7 and Appendix B). Edited data are flagged, rather than deleted from the Loran-C master file, permitting the engineer to modify the definitions of "acceptable" and "unacceptable" data as test experience accrues. Data must meet three criteria to be considered acceptable:

- Normal tracking -- indicated by the receiver mode
- Correct cycle -- verified by TD prediction using the site geodetic coordinates
- Consistency -- based on sample-to-sample outlier detection (typically 5% of samples are edited).

This modest editing procedure removes data which detract from the test objective of assessing grid warpage and instability. <u>In no instance are data edited based on the magnitude of grid warpage and instability</u>.

3.3 GRID WARPAGE

3.3.1 Data Base

Grid warpage is assessed using the Loran-C data collected with the FAATC Test Van in the approach areas of the Atlantic City, Philadelphia, Columbus, Worcester, and Rutland airports. Analysis is limited to the summer test data; the winter test data are discussed under grid instability in Section 3.4. The results are presented in terms of the rms cross-track error over all sites at an airport. The "heading" at a site is defined as the direction from the site to the ARP.

3.3.2 Model Performance

Loran-C coordinate conversion accuracy depends on three factors (see previous Fig. 3.1-1):

- Propagation Model
- Calibration Corrections
- Station Triad.

In this section, it is assumed that no calibration corrections are applied; accuracy results are given for different propagation models and station triads. The six master-dependent triads of the Northeast U.S. Loran-C chain are considered: MWX, MWY, MWZ, MXY, MXZ, and MYZ. The preferred or primary triad at an airport is the triad with the minimum Geometric Dilution of Precision (GDOP), as defined in Ref. 10. Although certain receivers operate in a master-independent mode and/or employ data from four or more stations in a least-squares solution, evaluation of these configurations is beyond the scope of the effort reported herein.

Figures 3.3-1a to 3.3-1e present the rms cross-track errors for the baseline, sea, land, mixed, and DMA propagation models, respectively.* Each figure shows the errors for all six station triads at all five airports. The baseline model satisfies AC-90-45A non-precision approach accuracy requirements for the primary triad at each airport (see Fig. 3.3-1a). One or two additional (alternative) triads are acceptable at Atlantic City, Philadelphia, and Worcester. However, only the primary triad is acceptable at Columbus and Rutland. The fact that the primary triad is not necessarily the most accurate triad is evidenced by the MWX (primary) and MWY (alternative) triads at Worcester. In this case, the lower GDOP for the primary triad is negated by higher grid warpage. A final observation to be made from Fig. 3.3-1a is that the baseline model satisfies AC-90-45A enroute and terminal accuracy requirements for three-to-six triads at each airport, as expected.

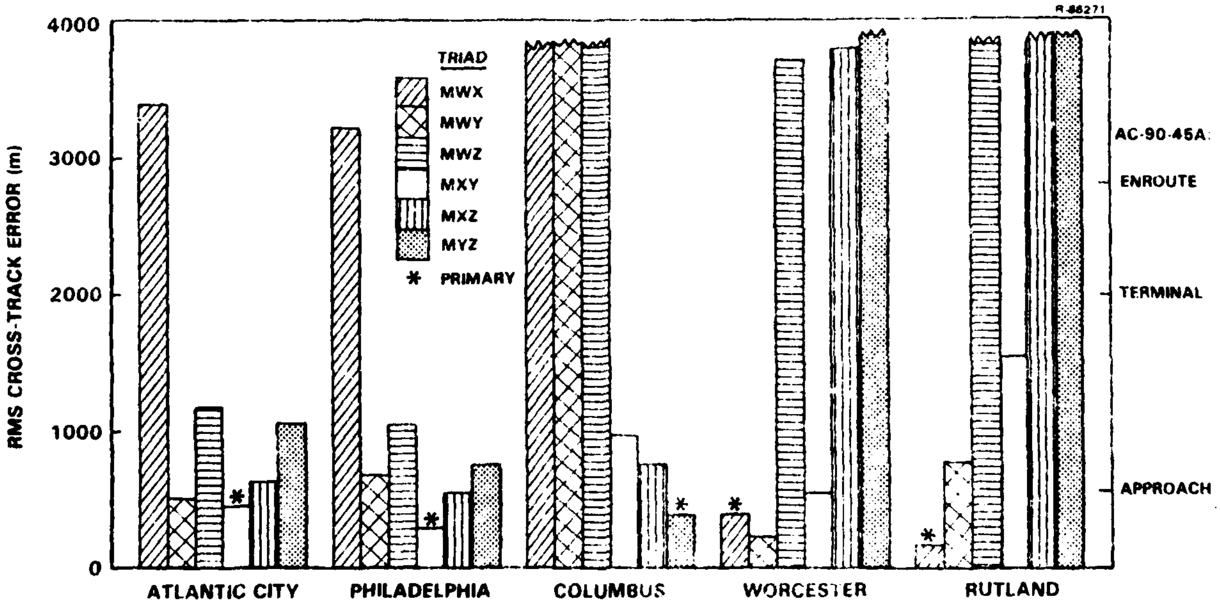


Figure 3.3-1a Baseline Model Performance

*Note scale difference between Fig. 3.3-1a and Figs. 3.3-1b to 3.3-1e.

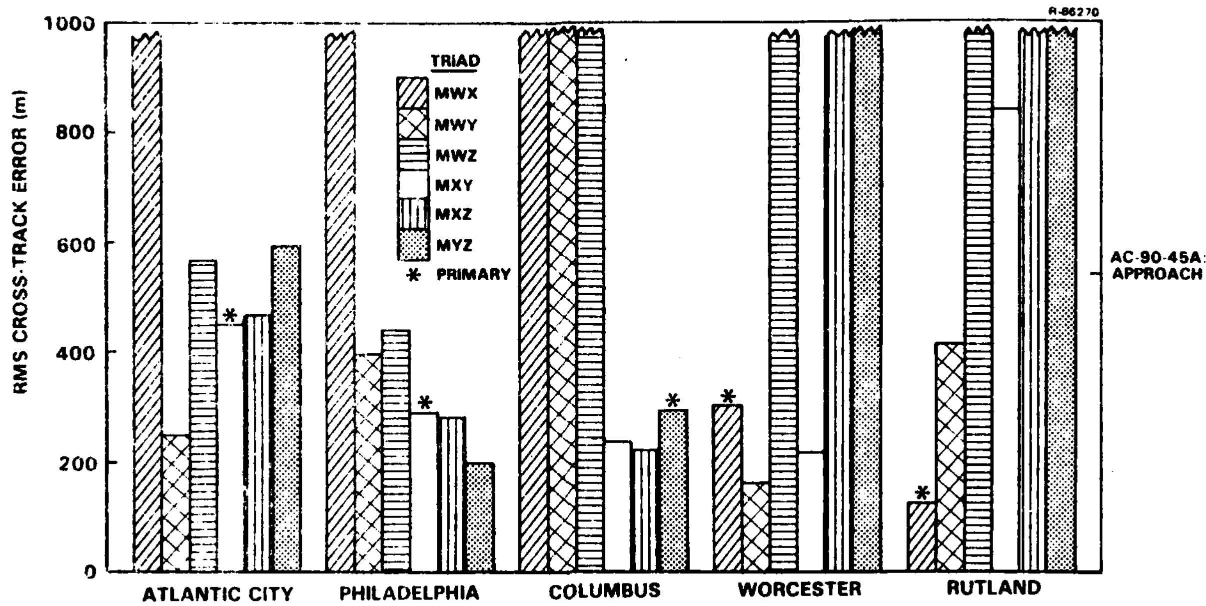


Figure 3.3-1b Sea Model Performance

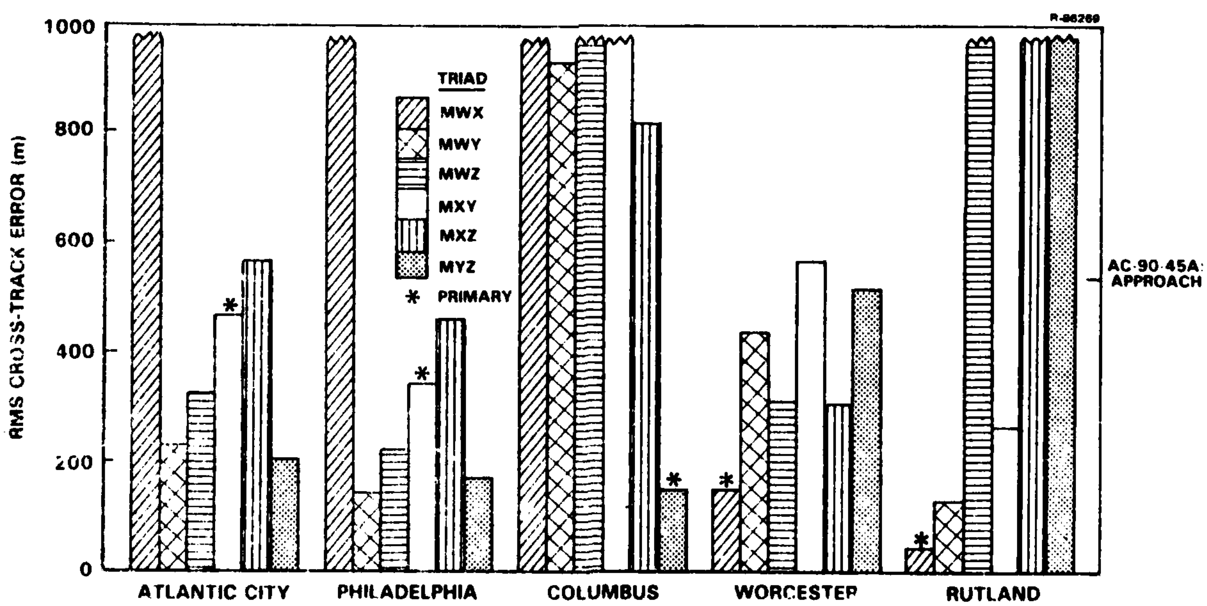


Figure 3.3-1c Land Model Performance

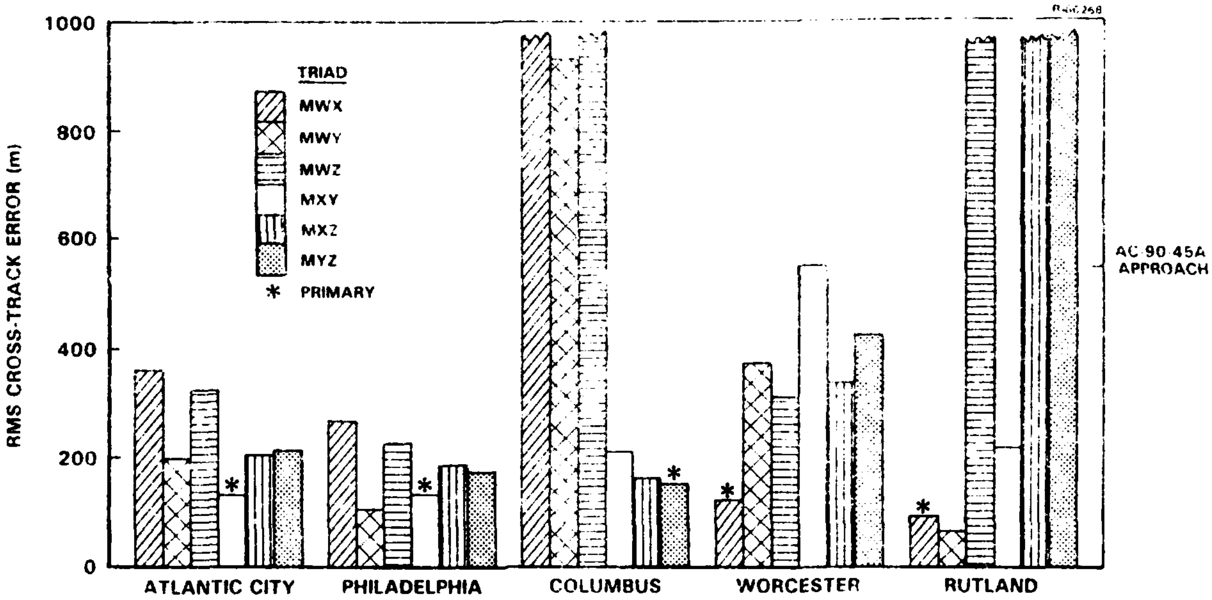


Figure 3.3-1d Mixed Model Performance

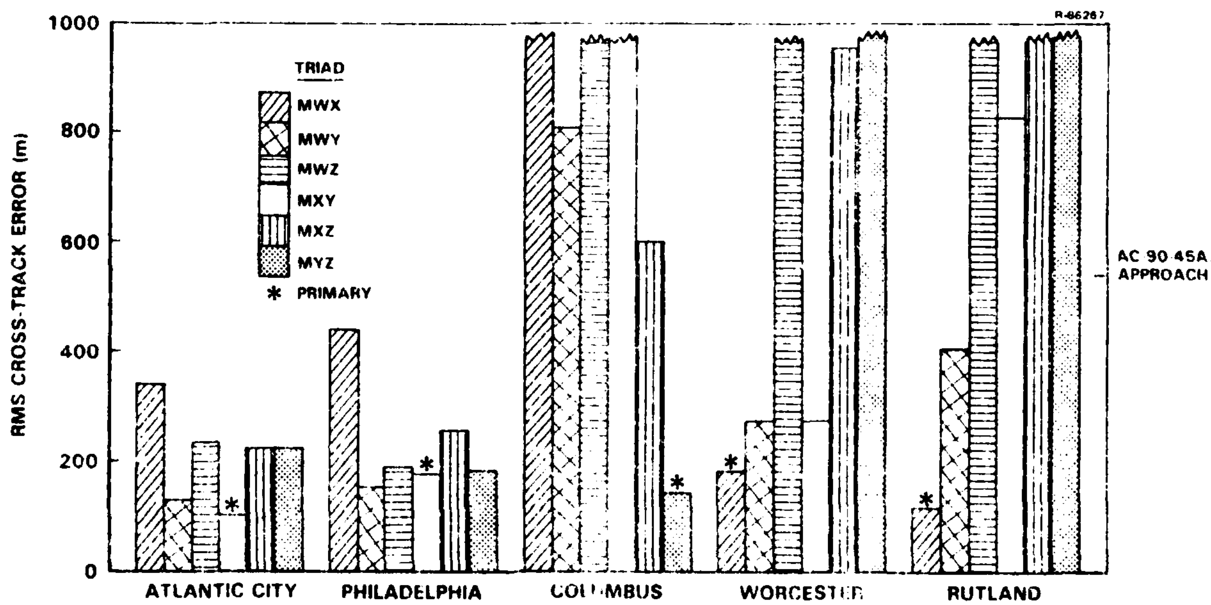


Figure 3.3-1e DMA Model Performance

Overall, the sea model and land model are significant improvements over the baseline model (see Figs. 3.3-1b and 3.3-1c). The number of acceptable triads at each airport increases or remains the same for these models, compared to the baseline model. When analyzed on the TD level, the accuracy of the models is typically found to be related to the relative percentage of land and sea water signal path segments. That is, the sea model tends to be most accurate for sea water paths and the land model tends to be most accurate for land paths. A contradiction to this rule is given by TDX for Columbus, however. The sea model is a factor of six more accurate in this case, even though the path from the master station is all land and the path from station X is 90-percent land.

The mixed and DMA models are significantly more accurate than the sea and land models (see Figs. 3.3-1d and 3.3-1e). Both models result in six acceptable triads at Atlantic City and Philadelphia. However, the mixed model is more accurate than the DMA model at the other three airports. This result is counter-intuitive, because the mixed model is based on fewer conductivity levels (two) than the DMA model (five). However, the DMA conductivity map is adjusted to match Loran-C data collected primarily at coastal locations. An unadjusted (theorectical) conductivity map would likely result in better performance at Columbus, Worcester, and Rutland.

A comparison of the five models is presented in Table 3.3-1. The mixed model results in the largest number of acceptable triads at each airport. It is important that more than one triad be acceptable at an airport, in the event of station failure (Ref. 24). For redundancy, at least one acceptable triad must remain when any single station fails. Only the mixed model provides redundant master-dependent triads at all five airports (barring master station failure). The sea model, for example, does not meet AC-90-45A requirements for any triad at Rutland if station W fails (see Fig. 3.3-1b).

TABLE 3.3-1

NUMBER OF TRIADS
SATISFYING AC-90-45A
NON-PRECISION APPROACH REQUIREMENTS

AIRPORT	PROPAGATION MODEL				
	BASELINE	SEA	LAND	MIXED	DMA
Atlantic City	2	3	4	6	6
Philadelphia	2	5	5	6	6
Columbus	1	3	1	3	1
Worcester	3	3	5	6	3
Rutland	1	2	3	3	2

3.3.3 Calibration Performance

Loran-C position errors at the Atlantic City Test Van sites, for the baseline model and MXY triad, are shown as vectors in Fig. 3.3-2. The dominant error component is a 700-m westerly bias. In practice, this bias could be calibrated by:

- Measuring TDX and TDY at a single site, known geodetically
- Subtracting the measured TDs from the model-predicted TDs for the site
- Applying the differences as calibration corrections throughout the airport approach area (see Fig. 3.1-1).

Bias calibration is a simple method to reduce Loran-C errors. Its importance is corroborated by the fact that the grid bias dominates random grid warpage for 140 of the 150 model/airport/triad combinations considered in Figs. 3.3-1a to 3.3-1e.

The rms cross-track errors for the baseline model, with bias calibration, are presented in Fig. 3.3-3. Bias

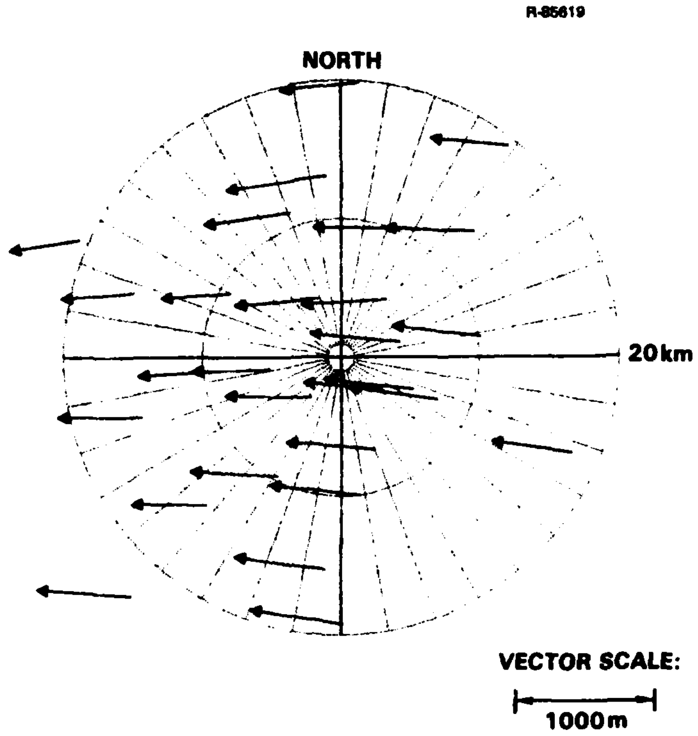


Figure 3.3-2 Loran-C Position Errors at the Atlantic City Test Van Sites

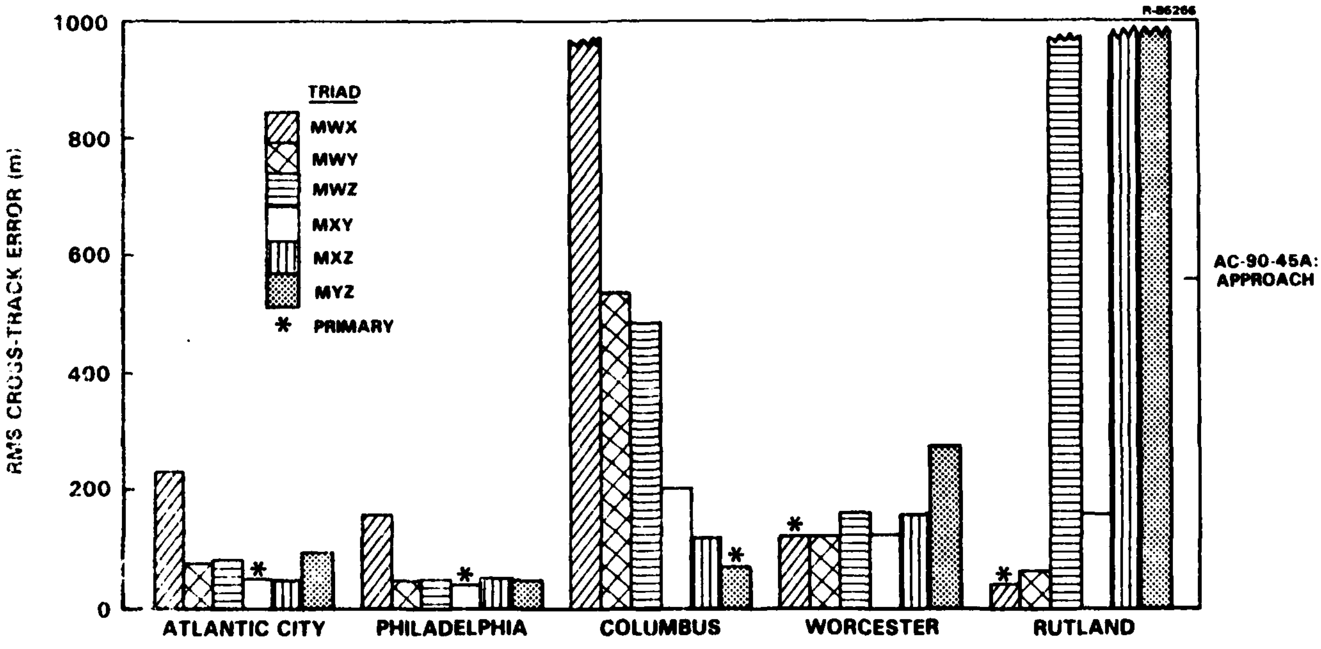


Figure 3.3-3 Baseline Model Performance with Bias Calibration

calibration results in a significant increase in the number of triads which are acceptable at each airport using the baseline model (see Table 3.3-2). Furthermore, the baseline model with calibration is more accurate than the mixed model without calibration. Bias calibration is thus recommended over sophisticated propagation models, to satisfy AC-90-45A non-precision approach requirements.

TABLE 3.3-2

BASELINE MODEL PERFORMANCE
WITH AND WITHOUT CALIBRATION

AIRPORT	NUMBER OF ACCEPTABLE TRIADS	
	WITHOUT CALIBRATION	WITH CALIBRATION
Atlantic City	2	6
Philadelphia	2	6
Columbus	1	5
Worcester	3	6
Rutland	1	3

The triads which do not satisfy AC-90-45A requirements in Fig. 3.3-3 are associated with poor geometry. Specifically, Columbus and Rutland are near the MW and MZ baseline extensions, respectively (see Fig. 2.2-3). Note that Worcester is further from the MZ baseline extension than is Rutland.

A decision to calibrate Loran-C leads naturally to the following question: are calibration corrections for one airport applicable to a neighboring airport? The position biases for the Atlantic City/Philadelphia and Worcester/Rutland airport pairs are similar in direction, but different in magnitude (see Table 3.3-3). It is found that if Atlantic City calibration corrections are used at Philadelphia or vice versa, all six triads are acceptable in both cases. However, if Worcester

TABLE 3.3-3

LORAN-C BIASES
FOR NEIGHBORING AIRPORTS

AIRPORT	TRIAD	LORAN-C BIAS*	
		MAGNITUDE (m)	APPROXIMATE DIRECTION
Atlantic City	MXY	700	West
Philadelphia	MXY	500	West
Worcester	MWX	600	North
Rutland	MWX	300	North

*Baseline model assumed.

rather than Rutland calibration corrections are used at Rutland, the number of acceptable triads is reduced from three to one. Similarly, if Rutland rather than Worcester calibration corrections are used at Worcester, the number of acceptable triads is reduced from six to three. Non-local calibration in these cases results in the same number of acceptable triads as no calibration. Therefore, Worcester and Rutland are a pair of airports, separated by 180 km, for which non-local calibration is inadequate. However, non-local calibration is adequate for Atlantic City and Philadelphia, which are separated by 80 km. Generalization of these results is not advisable due to the uncertain spatial variability of ground conductivity.

3.4 GRID INSTABILITY

3.4.1 Data Base

Test Van, Airport Monitor, and Fixed-Site Monitor data are all used to assess grid instability (see Table 3.4-1). For analysis purposes, grid instability is divided into two components:

TABLE 3.4-1

GRID INSTABILITY DATA BASE

INSTABILITY COMPONENT	TEST FACILITY	NOMINAL SAMPLING	
		INTERVAL	DURATION
Short-Term	Test Van	1 min	30 min
	Airport Monitor	1 min	2 wk
	Airport Monitor	10 sec	2 hr
Seasonal	Test Van	6 mo	1 yr
	Fixed-Site Monitor	15 min	1 yr

- Short-term instability -- over periods less than two weeks
- Seasonal instability -- over the entire year.

The short-term data serve to validate the grid warpage analysis methodology and to assess the need for high-rate differential Loran-C. The seasonal data are used to assess the need for "low-rate differential Loran-C", more descriptively called "periodic calibration". The grid instability data are presented graphically as TD time series (histories) and interpreted in terms of the rms cross-track error where appropriate. A scale factor of 300 m/μsec is a useful "rule-of-thumb" for converting TD variations to rms cross-track errors, for the primary triad at an airport (GDOP $\tilde{-}$ 1). The scale factor is multiplied by GDOP for other triads; the largest GDOP of practical interest is 10.

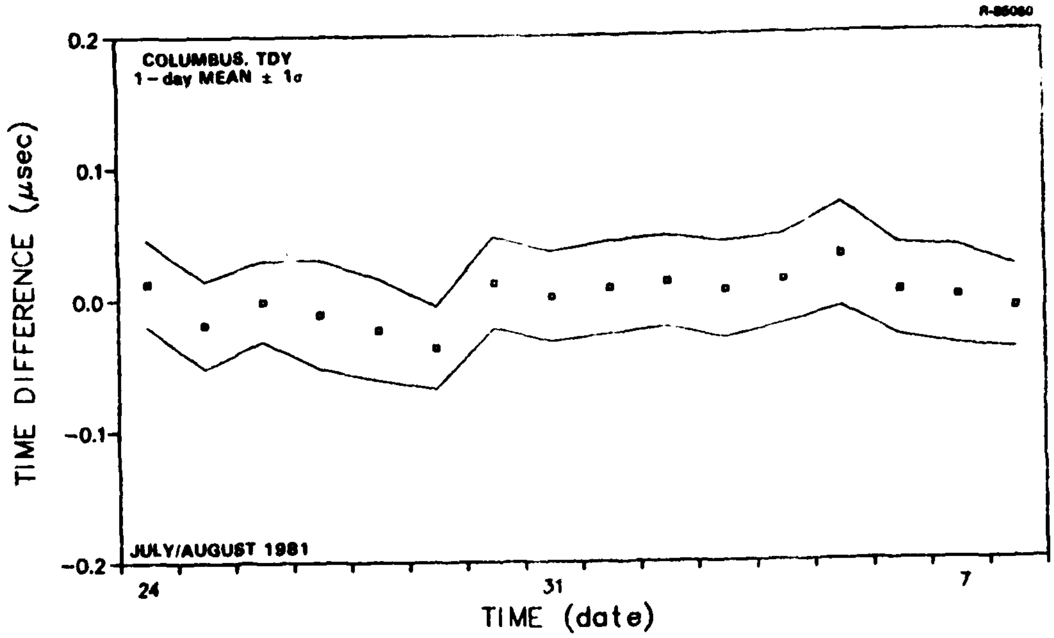
3.4.2 Short-Term Instability

Test Van data are recorded at each site for 30 min, using a 1-min sampling interval. The standard deviation of

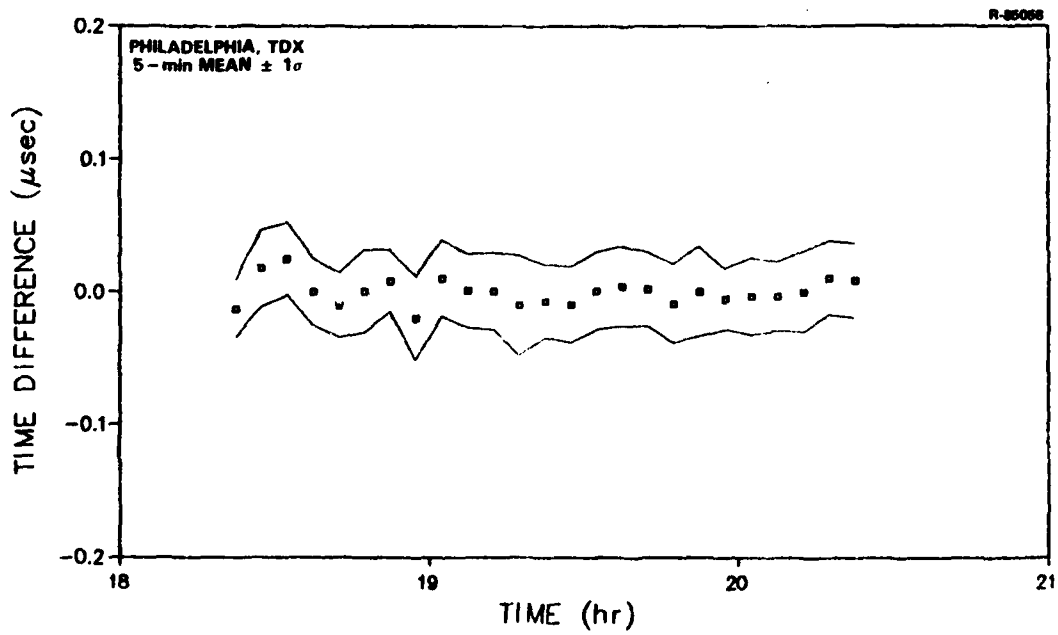
the TD data ranges from 0.01 μsec for high SNR conditions (5 to 15 dB) to 0.05 μsec for low SNR conditions (-5 to -15 dB), indicating that TD instability over a 30-min period is primarily noise-induced "jitter". The effect of the jitter is minimized by averaging in computing the site TD used for grid warpage assessment.

Airport Monitor data are recorded at each airport during the period of Test Van operations (nominally, 2 wk), primarily using a 1-min sampling interval. A typical TD time series based on 1-day smoothing is shown for the Columbus Airport Monitor in Fig. 3.4-1a. Each point on this graph is the mean of all samples collected during the indicated day (10-hr period). The solid lines show the daily standard deviation ($\pm 1\sigma$). The standard deviation is consistent over the 16-day period and equals the noise level expected for the Micrologic ML-220 receiver ($\tilde{}$0.03 μsec). This suggests that apparent grid instability over a 10-hr period is primarily noise-related. There is also a propagation-related day-to-day variation in the mean TD (< 0.1 μsec). Because this variation is expected to be experienced over the entire airport approach area, the Airport Monitor TD data are used to "synchronize" the Test Van TD data collected at different sites at different times. Grid warpage on the rms cross-track error level is found to be virtually identical with and without synchronization.

Airport Monitor data are also recorded for selected periods of approximately 2 hr, using a 10-sec sampling interval. The 10-sec data are expected to be representative of short-term instability encountered in the airborne environment. A typical TD time series based on 5-min smoothing is shown for the Philadelphia Airport Monitor in Fig. 3.4-1b. Each 5-min period is interpreted as the total period of an aircraft approach, starting at a distance of 20 km from the airport. The TD standard deviation over the 5-min interval is typically 0.03 μsec.



a) 1-day Smoothing of 1-min Data



b) 5-min Smoothing of 10-sec Data

Figure 3.4-1 Typical Airport Monitor TD Time Series

If calibration corrections are applied before initiating approach (e.g., provided during ground-to-air voice communications), the resulting rms cross-track errors range from 15 m (GDOP = 1) to 150 m (GDOP = 10). It is concluded that calibration corrections do not have to be updated during an aircraft approach. High-rate differential Loran-C employing a telemetry link is thus not required.

3.4.3 Seasonal Instability

For simplicity, it is preferred that a single model or calibration be applicable for the entire year and from year to year. The model and calibration performance results presented in Section 3.3 are based on Test Van data collected in the "summer" (May to October). The TD biases measured in the "winter" (February to March) differ from those measured in the summer (see Table 3.4-2). However, the candidate propagation models result in the same number of acceptable triads in the winter as in the summer. Similarly, calibration corrections determined from the summer data result in the same number of acceptable triads in the winter as in the summer. Thus, the seasonal shift in the bias measured by the Test Van is not sufficiently large to warrant separate summer and winter models or calibration corrections.

The Test Van data are not expected to represent a worst case because:

- Peak-to-peak instability over the entire year is not measured
- Airport/SAM hyperbolic distances are less than 150 nm for the primary triad at each airport tested (see Section 2.4).

The Fixed-Site Monitor data collected every 15 min for 1 yr at London, KY are expected to be more representative of worst-case

TABLE 3.4-2

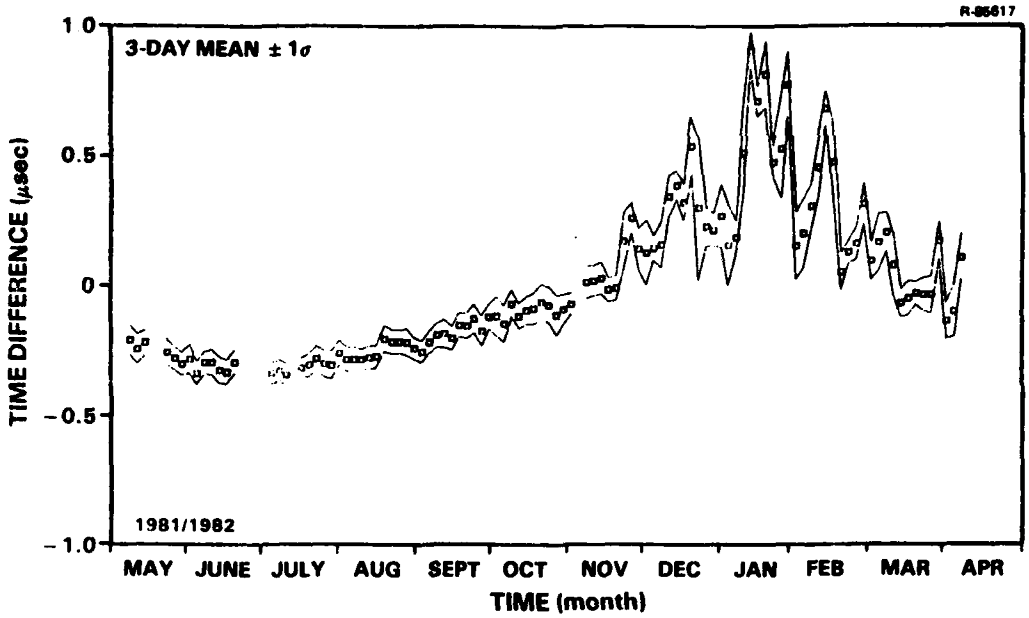
SEASONAL TD BIAS SHIFTS
MEASURED BY TEST VAN

AIRPORT	TD BIAS SHIFT* (μsec)			
	TDW	TDX	TDY	TDZ
Atlantic City	0.2	0.0	-0.1	0.4
Philadelphia	0.1	-0.1	0.0	0.3
Columbus	0.6	0.2	-0.2	-0.5
Worcester	0.1	0.2	0.1	0.2
Rutland	0.1	-0.1	-0.1	0.0

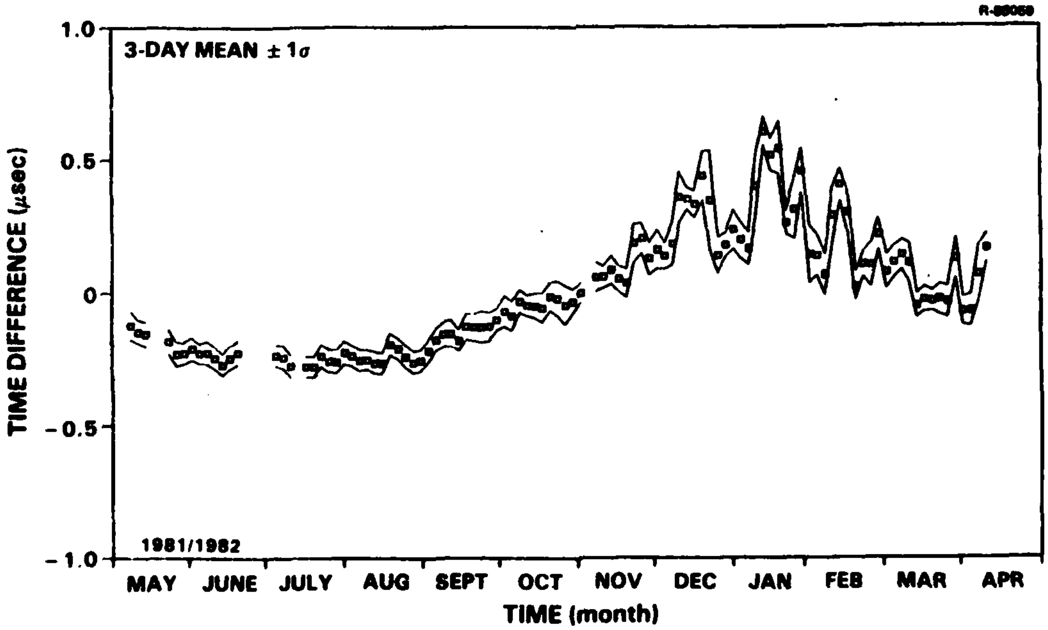
*(Winter TD) - (Summer TD), averaged over all sites.

seasonal instability. TDY and TDZ time series based on 3-day smoothing of the London data are presented in Fig. 3.4-2. The peak-to-peak variation in TDY over the test year is nearly 1.5 μsec (360 m in the LOP), larger than observed in any Loran-C test reviewed in Ref. 6. For example, the peak-to-peak variation in TDX at Burlington, VT was 0.8 μsec between October 1979 and September 1980 (Ref. 4). Both TDY and TDZ at London vary slowly between May and October, but exhibit large excursions over weekly time periods between November and April (see Fig. 3.4-2). This observation is consistent with the Burlington, VT test data and with data collected in the St. Marys River mini-chain (Refs. 4 and 11). Also note that TDY and TDZ variations are highly correlated, suggesting that they are caused by the same physical mechanism (see Section 3.4.4).

To relate the London data to AC-90-45A accuracy requirements, it is assumed that grid warpage for the London airport is a pure spatial bias and that seasonal variations in the bias are given by the Fixed-Site Monitor data. It is further assumed that calibration corrections based on the yearly



a) TDY



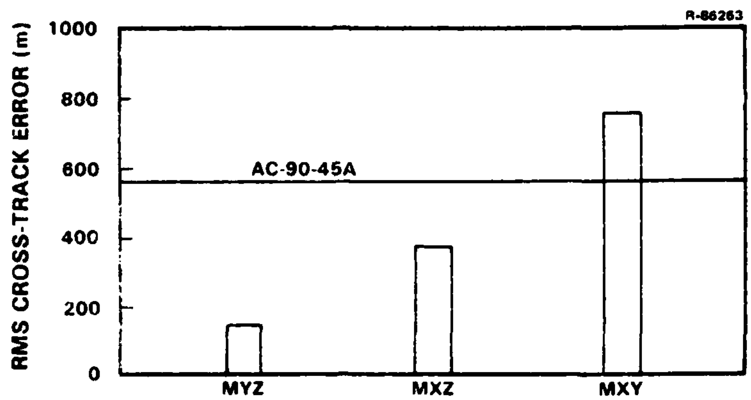
b) TDZ

Figure 3.4-2 London Fixed-Site Monitor TD Time Series

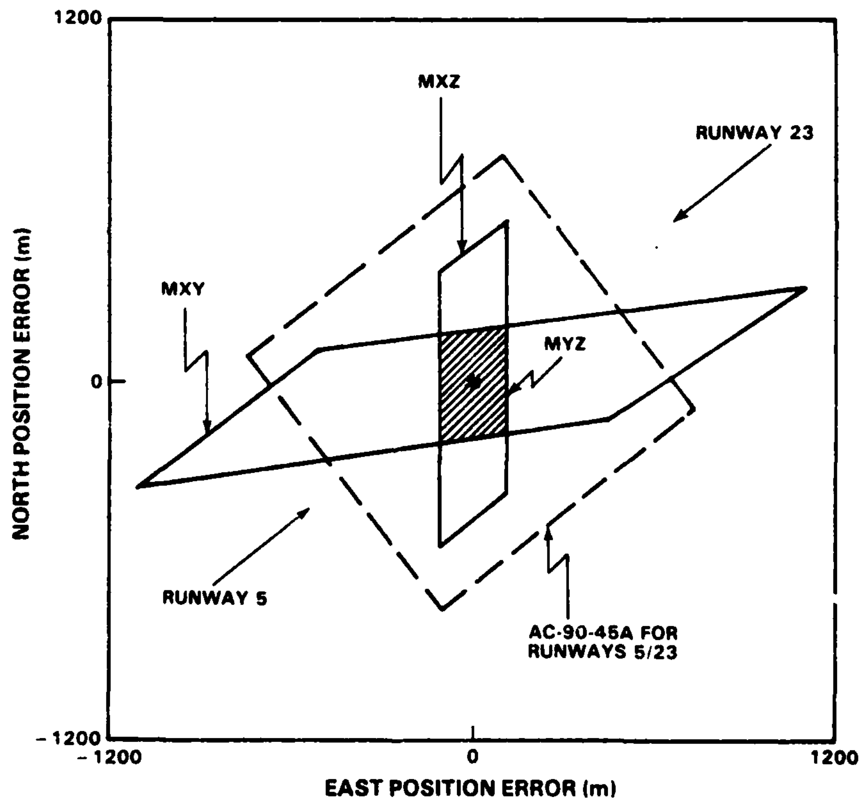
mean TDs are applied. In practice, calibration corrections obtained in the spring or fall could be used to approximate the yearly mean (see Fig. 3.4-2). The worst-case error then occurs at the summer/winter extremes. The resulting summer/winter rms cross-track error is 175 m for the MYZ triad, well within AC-90-45A non-precision approach accuracy requirements (550 m).

The MYZ triad is the <u>primary</u> triad for London. The TDX data are not of sufficient quality to determine the performance of the MXY and MXZ triads, the two additional triads required for redundancy. However, to demonstrate the impact of GDOP on seasonal instability, it is <u>assumed</u> that the peak-to-peak variation in TDX is 1.0 μsec (see Section 3.4.4 for justification), compared to the observed values of 1.5 μsec for TDY and 1.0 μsec for TDZ. The same assumptions as above, regarding pure bias errors and spring/fall calibration corrections, are made here. The resulting summer/winter rms cross-track errors are shown in Fig. 3.4-3a. The MXY triad does not satisfy AC-90-45A requirements in this example.

Another method of displaying the errors is given in Fig. 3.4-3b. Each parallelogram in this figure encompasses the position errors for the entire year, for the indicated triad. It is contructed by intersecting two "swaths", each representing the errors in one LOP. The MXY parallelogram lies partly <u>exterior</u> to the AC-90-45A error bounds for Runways 5 and 23 at London. Based on this hypothetical but realistic example, it is expected that use of a single set of calibration corrections over the entire year will not be adequate for certain triads at certain airports. In these cases, it is conceivable that calibration corrections will have to be updated as often as daily to accommodate the rapid TD excursions which occur in winter. However, additional grid instability data from a network of Fixed-Site Monitors are required before definitive conclusions can be drawn regarding update requirements.



a) RMS Cross-Track Errors



b) Error Parallelograms

Figure 3.4-3 Loran-C Performance at London Airport (Based on Hypothetical TDX Instability)

3.4.4 Physical Mechanism

The most important physical parameter responsible for seasonal grid instability is expected to be the vertical lapse rate -- i.e., the gradient of the atmospheric refractivity with altitude (Refs. 27 and 28). The vertical lapse rate is highly correlated with surface refractivity, which is related to pressure, temperature, and humidity along the signal paths (Ref. 29). A particularly high correlation between grid instability and the dry term of surface refractivity has been observed by others (e.g., Ref. 12).

To verify this physical mechanism, seasonal meteorological data from the four National Weather Service Stations shown in Fig. 3.4-4 are used to compute the average refractivity dry term for the London/MYZ signal paths. The correlation coefficient between the London TDY/TDZ data and the refractivity dry term is 0.97 (see Fig. 3.4-5), suggesting that seasonal instability is caused almost entirely by vertical lapse rate variations.

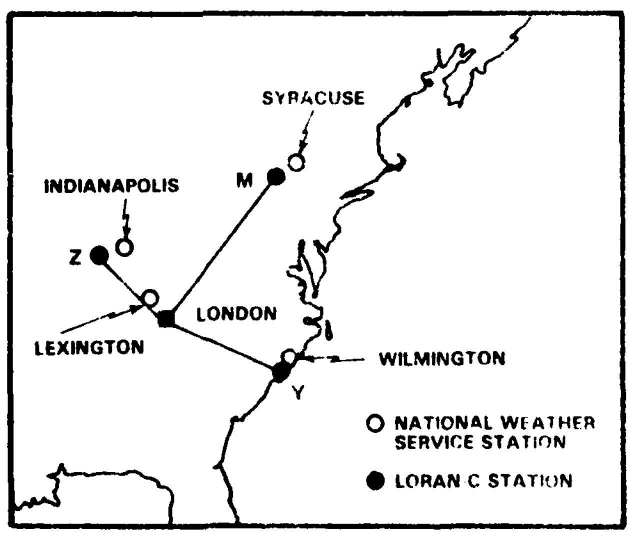


Figure 3.4-4 Selected National Weather Service Stations

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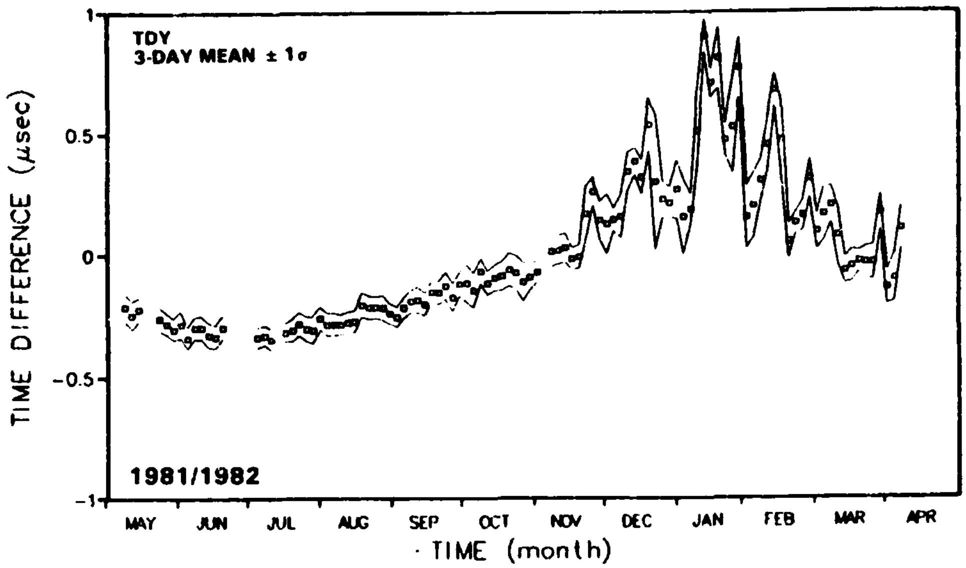
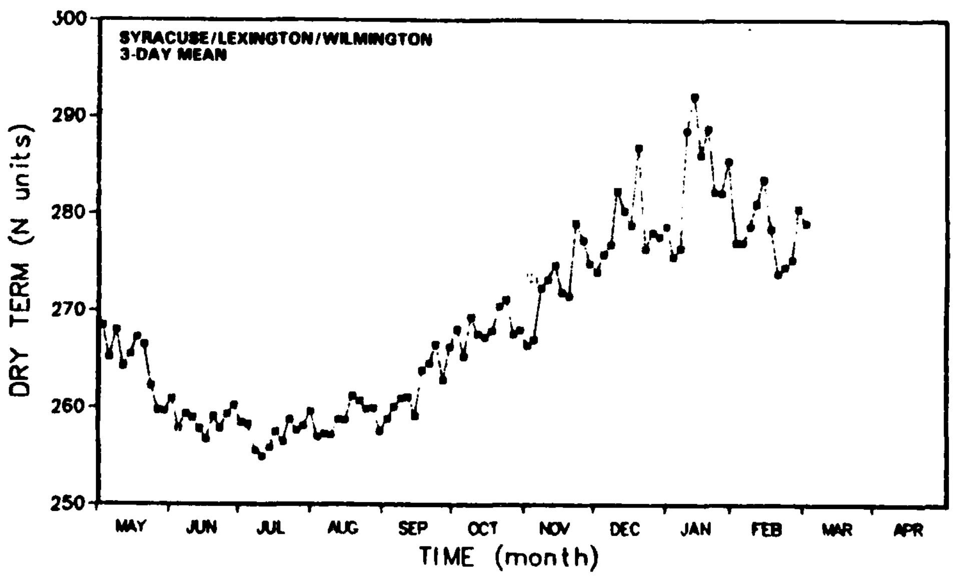


a) TDY



b) Refractivity Dry Term

Figure 3.4-5 High Correlation Between London TD Data and Refractivity Dry Term

An examination of U.S. Coast Guard chain records for the test year shows that grid instability at the SAM is within the tolerances governing chain control (±0.1 μsec). Grid instability elswhere in the chain coverage area is expected to be nearly proportional to the hyperbolic distance from the SAM. This is confirmed by the London data. Specifically, the ratio of the peak-to-peak variations in TDY and TDZ (1.5 μsec/1.0 μsec) is approximately equal to the ratio of the corresponding hyperbolic distances (400 nm/250 nm). This relationship is justification for expecting a 1.0 μsec peak-to-peak variation in TDX, for which the hyperbolic distance is 250 nm (see Section 3.4.3). Additional data from several Fixed-Site Monitors are required to validate the relationship.

3.5 LORAN-C CERTIFICATION

Based on the FAATC test results, it is concluded that Loran-C certification procedures for non-precision approach must account for grid warpage and instability. Grid warpage is an issue at all airports, but grid instability is an issue at only certain airports. Additional Fixed-Site Monitor data are required to identify regions where grid instability is significant.

First, consider airports where instability is not a problem. In this case, triad redundancy can be achieved by using a single mixed-path model or calibration for the entire year. Calibration is somewhat more accurate than mixed-path models and less expensive to implement in a receiver. However, potential disadvantages of calibration are the increased pilot workload and decreased reliability associated with manual insertion of calibration corrections. Pilot workload is not a problem if the corrections are inserted before departure. Reliability can be maximized by storing the corrections on a

magnetic card or in the receiver memory itself. Models and calibration both require Loran-C data collection -- either to validate model accuracy or to determine calibration corrections. Model/calibration accuracy cannot be guaranteed unless data are collected at every airport of interest. Cost savings realized by "skipping" airports are overshadowed by uncertainty in Loran-C accuracy at these airports. Data collection requirements at an airport are not severe: it is likely that recording of Loran-C TDs for 30 min at a single site whose geodetic coordinates are known will be sufficient. For example, data could be collected on the ground during routine airport inspections. Calibration corrections could be included as annotations on airport charts, as shown in Fig. 3.5-1.

R-87661

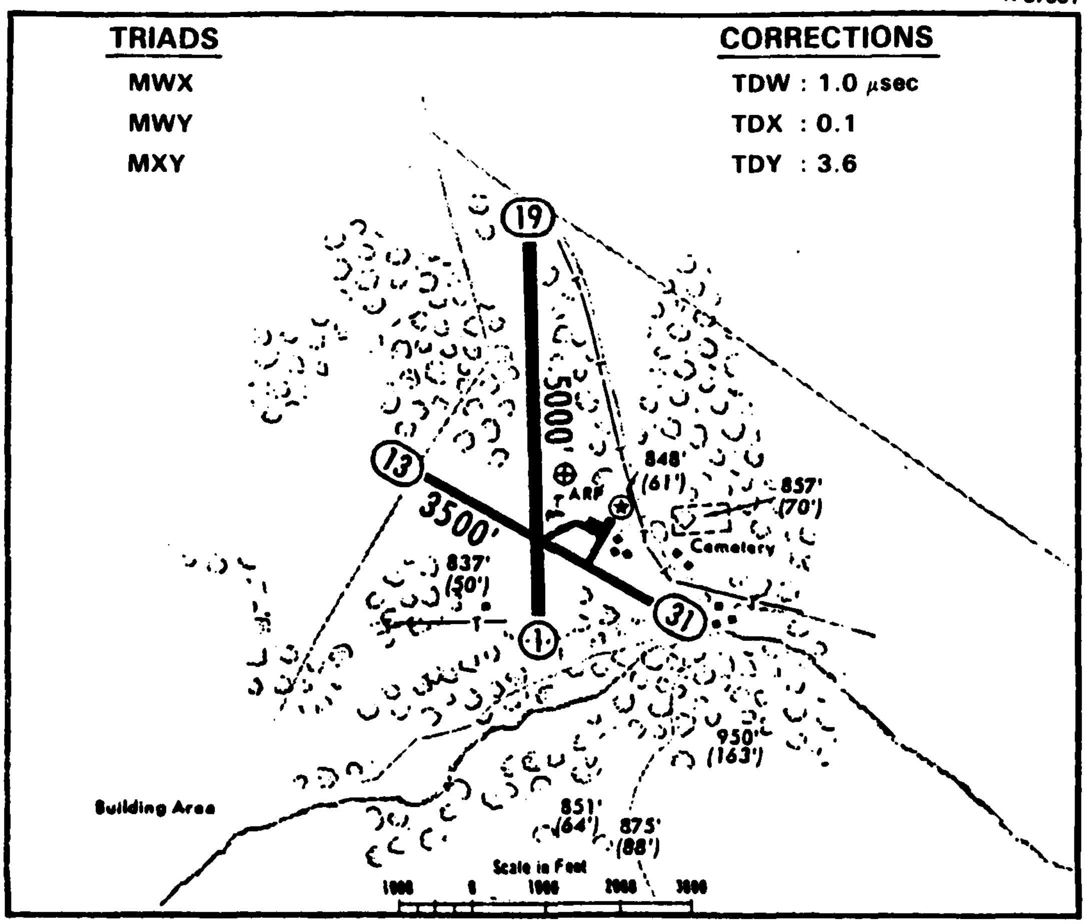


Figure 3.5-1 Example of Annotated Rutland Airport Chart

Next, consider airports where grid instability is judged to be a problem. Periodic calibration is required in this case; the issue of models vs calibration is irrelevant. "Average" calibration corrections for the year are determined using data collected in the spring or fall. These data are collected at every airport of interest, as described previously. The calibration corrections are updated periodically based on data collected at a Fixed-Site Monitor servicing several airports. The "region-of-influence" of the Fixed-Site Monitor cannot be identified from currently available test data. The updated calibration corrections are furnished to the pilot as often as needed to satisfy AC-90-45A requirements, e.g., in weekly printed notices or daily verbal messages. This function could be met by a Notice-to-Airmen facility, established to also monitor Loran-C chain status and signal quality.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Results of TASC analyses of Loran-C ground-based test data collected by the FAA Technical Center (FAATC) for the FAA Systems Research and Development Service are documented in this report. The FAATC tests are motivated by the Federal Radionavigation Plan and focus on the non-precision approach flight phase. The objective of the tests is to isolate and assess spatial warpage and temporal instability in the Loran-C hyperbolic navigation grid. Grid warpage is assessed using Time Difference (TD) data collected with the FAATC Test Van at approximately 25 sites within 20 km of each of five airports. Grid instability is assessed using data recorded by stationary monitors operated for two-to-three weeks at each airport and for one year at London, KY.

Five propagation models, representing different levels of receiver software sophistication, are evaluated without calibration corrections. The number of station triads satisfying FAA Advisory Circular AC-90-45A requirements is given in Table 4.1-1 for each model and airport tested. It is concluded that the baseline model, a simple model based on pure atmospheric propagation, provides at least one acceptable triad at each airport. However, the baseline model provides only one acceptable triad at Columbus and Rutland. The sea model and land model, which assume all sea water and all average land paths, respectively, tend to provide a larger number of acceptable triads than the baseline model. However, only the mixed model, which is based on mixed land/sea paths (two conductivity levels) and Millington's method, results in a

TABLE 4.1-1

NUMBER OF TRIADS
SATISFYING AC-90-45A REQUIREMENTS

AIRPORT	PROPAGATION MODEL WITHOUT CALIBRATION					BASELINE MODEL WITH CALIBRATION
	BASELINE	SEA	LAND	MIXED	DMA	
Atlantic City	2	3	4	6	6	6
Philadelphia	2	5	5	6	6	6
Columbus	1	3	1	3	1	5
Worcester	3	3	5	6	3	6
Rutland	1	2	3	3	2	3

redundant set of triads at each airport.* A mixed-path model based on the Defense Mapping Agency (DMA) five-level conductivity map is less accurate, especially at Columbus. Although this is attributed to the fact that the DMA conductivity map is adjusted to match coastal data, it illustrates that model sophistication does not guarantee model accuracy.

The dominant Loran-C error, the grid bias, can be removed by calibration. This is accomplished by applying TD calibration corrections based on data collected previously at the airport. The baseline model with calibration provides at least as many acceptable triads as the mixed model without calibration (see Table 4.1-1). Calibration corrections based on Atlantic City data are found to be applicable to Philadelphia (80 km away) and vice versa. However, Worcester calibration corrections are not applicable to Rutland (180 km away) or vice versa. Based on these results and the spatial variability of ground conductivity, it is concluded that Loran-C accuracy cannot be guaranteed unless calibration data are collected at every airport of interest. However, it will likely be

*That is, failure of a single station does not result in failure of all acceptable triads.

sufficient to record the Loran-C data for 30 min at a single airport site whose geodetic coordinates are known.

Grid instability is found to be negligible during the 5-min period required for aircraft approach. High-rate differential Loran-C employing a telemetry link is thus not required. Seasonal instability based on Test Van data collected twice during the year, between May and October and between February and March, is also found to be negligible. However, TDY and TDZ time series recorded at London, KY from May 1981 to April 1982 suggest that seasonal instability is a potential problem. For example, the peak-to-peak variation in TDY is 1.5 μsec (360 m in the LOP) over the test year (see Fig. 4.1-1). A single set of calibration corrections based on spring or fall data satisfy AC-90-45A requirements for the primary triad (MYZ) at London. However, based on reasonable assumptions regarding TDX variations (actual data are not available), it is found that a single calibration is not adequate for the MXY triad, one of the triads required for redundancy. Therefore, it is expected that periodic calibration will be necessary for certain triads at certain airports.

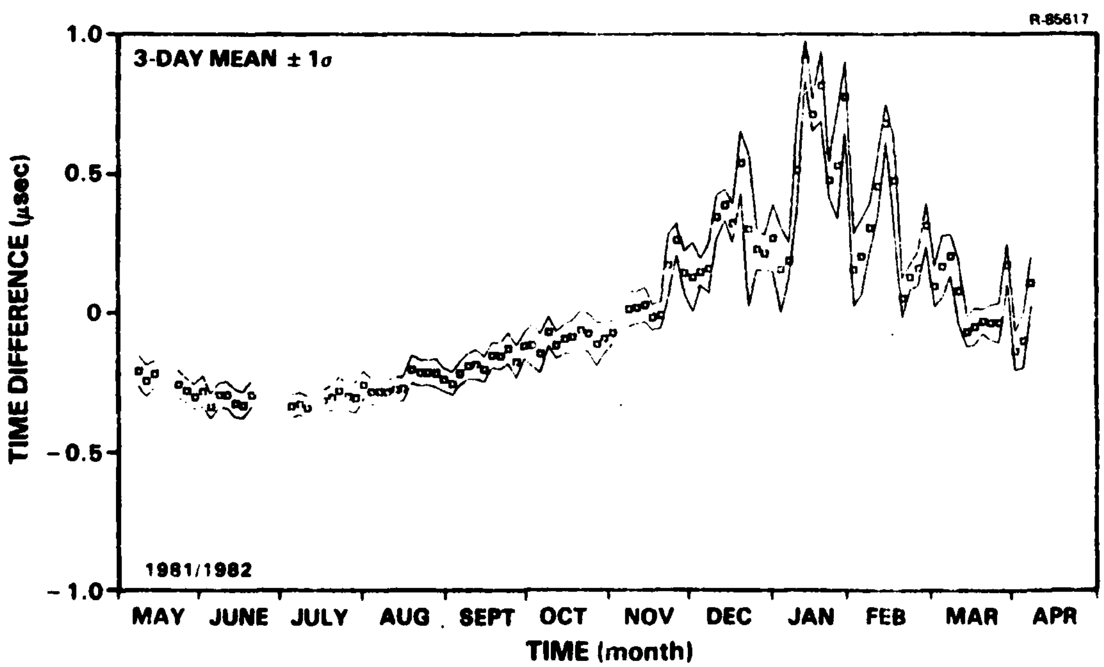


Figure 4.1-1 TDY Time Series at London Fixed-Site Monitor

Based on the FAATC test results, it is thus concluded that Loran-C certification procedures for non-precision approach must account for grid warpage and instability. Grid warpage is an issue at all airports, but grid instability is an issue at only certain airports. Additional Fixed-Site Monitor data are required to identify regions where grid instability is significant.

4.2 RECOMMENDATIONS

It is recommended, contingent on the results of other FAA investigations (e.g., pertaining to coverage and cost), that Loran-C be considered as a supplement to VOR/DME for non-precision approach. "Blanket" Loran-C approval over large regions is not recommended for non-precision approach, as it is for enroute and terminal flight. Comprehensive methods for design and specification of each runway approach procedure must be developed. The three aspects of approach procedure establishment are: receiver hardware/software validation, approach pattern/chart development, and flight testing.

Based on the FAATC test results, it is recommended that the following receiver software validation procedure be adopted:

- Measure the TDs at an airport site whose geodetic coordinates are known (an accepted standard receiver is used here)
- Convert the measured TDs to a position fix, using the receiver software under test
- Approve the software without calibration corrections if the position fix is near enough to the known site position to satisfy AC-90-45A requirements
- Retest the software with calibration corrections if the position fix is out of tolerance

- Require that calibration corrections be used and periodically updated at airports where grid instability is a problem.

Before Loran-C approach procedures can be widely established, tests must be conducted to answer three remaining questions:

- How severe is grid warpage in extreme environments such as the Rocky Mountains, Alaska, and coastal regions?
- What regions in each chain coverage area are adversely affected by grid instability and how many monitors are required to determine calibration corrections in these regions?
- Are grid warpage and short-term instability in the airborne environment significantly different than on the ground?

These questions can be answered using the Test Van, a network of Fixed-Site Monitors, and a small number of flight tests, respectively.

APPENDIX A
LITERATURE REVIEW SUMMARY

Several Loran-C grid warpage and instability tests have been conducted during the past decade, some focusing on specific applications and others on basic research. Key features of these tests are presented in Tables A-1 and A-2. Test scenarios and test results are summarized in Ref. 6 and detailed in the original reports.

TABLE A-1

GRID WARPAGE TESTS

T-5127

SPONSORING/PERFORMING ORGANIZATIONS	COMPLETION DATE	LORAN-C CHAIN	SITE LOCATIONS	NUMBER OF SITES	COVERAGE (km)	REF.
U.S. Coast Guard/TASC	1979	U.S. West Coast	Pacific Coast	27 Land 23 Sea	1500	13
U.S. Air Force/MITRE	1979	Southeast U.S.	Eglin AFB, Florida	126	80x140	14
U.S. Coast Guard/TASC	1978	St. Marys River	Northern Michigan	25	120	15
Canadian Hydrographic Service/ Kaman TEMPO	1978	Northeast U.S.	Great Lakes Region	10	1000	16
U.S. Coast Guard/Kaman TEMPO	1978	U.S. West Coast	California and Nevada	8 on Radial 14 in Harbor	800 40	17
Canadian Hydrographic Service	1977	Canadian West Coast	Vancouver Island Region (Offshore)	200	1000	18
U.S. Army	1975	U.S. East Coast	Central New Jersey	61	100x100	19
U.S. Army	1973	U.S. East Coast	Montauk Point on Long Island	54	3x8	20
Commerce Dept.	1972	U.S. East Coast	Clemson, South Carolina	74	100x100	21

TABLE A-2

GRID INSTABILITY TESTS

T-5128

SPONSORING/PERFORMING ORGANIZATIONS	COMPLETION DATE	LORAN-C CHAIN	SITE LOCATIONS	NUMBER OF SITES	TEST DURATION	REF.
FAA/TSC	1980	Northeast U.S.	Vermont	3	14 mo	4
U.S. Coast Guard/TASC	1980	St. Marys River	Northern Michigan	3	1 yr	11
Canadian Hydrographic Service/ Kaman TEMPO	1978	Northeast U.S.	Great Lakes Region	3	3 wk	16
U.S. Coast Guard/Kaman TEMPO	1978	U.S. West Coast	California and Nevada	4	10 mo	17
U.S. Coast Guard/Magnavox	1977	U.S. East Coast	Indiana, Ohio, and Washington, D.C.	3	3 mo	12
U.S. Coast Guard/Internav	1973	U.S. East Coast	Along Delaware River	8	2 mo	22
U.S. Navy/Sperry Systems Management	1971	U.S. East Coast	Loran-C Transmitters	3	1 yr	23

APPENDIX B

LORAN-C DATA MANAGEMENT SYSTEM

The contract deliverables associated with the Loran-C Data Management System developed to process the FAATC test data are listed in Table B-1. The Data Management System is comprised of a Preprocessor, Processor, and Postprocessor, as shown in Fig. B-1.

TABLE B-1

CONTRACT DELIVERABLES ASSOCIATED WITH DATA MANAGEMENT SYSTEM

DELIVERABLE ITEM	DESCRIPTION	REF.
A.1	Data Management System Design Briefing	30
A.2	Preprocessor Software Requirements	31
A.3	Processor Software and Documentation	32
A.4	Loran-C Data Base Tapes	--
A.5	Postprocessor Software Requirements	33

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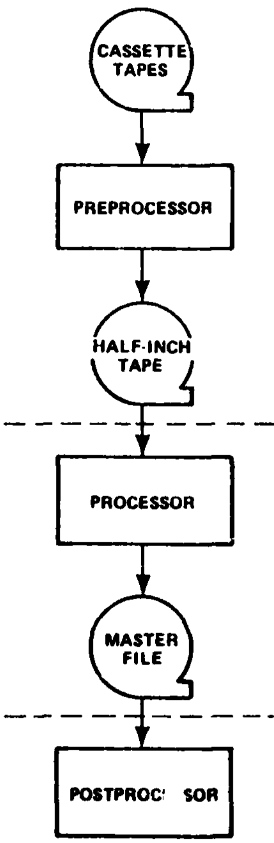

FUNCTIONS	RESPONSIBILITY	
	TASC	FAATC
■ TAPE CONVERSION ■ FORMAT CHECKS ■ FILE LABELING ■ TAPE LAYOUT	■ SOFTWARE REQUIREMENTS ■ CONSULTATION	■ SOFTWARE DEVELOPMENT ■ SOFTWARE UTILIZATION ■ HALF-INCH TAPES (FURNISHED TO TASC)
■ FILE MERGING ■ FILE SORTING ■ REFORMATTING ■ EDITING ■ "QUICK-LOOK" TABLES/GRAPHS	■ SOFTWARE DEVELOPMENT ■ SOFTWARE UTILIZATION ■ MASTER FILE DELIVERY ■ SOFTWARE DELIVERY ■ DOCUMENTATION ■ TRAINING	■ INFORMATION REGARDING FAATC COMPUTER FACILITY
■ STATISTICAL TABLES ■ GRAPHS	■ SOFTWARE REQUIREMENTS ■ TASC SOFTWARE DEVELOPMENT ■ CONSULTATION	■ FAATC SOFTWARE DEVELOPMENT

Figure B-1 Loran-C Data Management System

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